

Experimental Determination of Ground System Performance for HF Verticals

Part I

Test Setup and Instrumentation

This description of the test setup used by the author for a series of experiments sets the stage for a series of articles describing his results.

HF verticals located on or near ground are a perennial topic among amateurs. Over the past several years this discussion has been illuminated (and in some cases obscured!) by the advent of really good modeling software based on NEC (numerical electromagnetic code). This has resulted in a vast literature on antennas using the results of modeling. However, these results are not without some controversy. In particular the relative merits of a large number of buried radials versus a few elevated radials has been especially contentious. What has been missing from the discussion are careful field measurements done with good instrumentation and technique to see if the NEC predictions actually hold up in the real world. To address this problem I performed a series of field experiments, over a period of a year, to examine how different ground system arrangements affected the behavior of a vertical antenna and to see if field measurements on a real antenna would correlate with NEC modeling.

The results of these experiments will be presented in a series of *QEX* articles. There is no pretence that these experiments will answer all questions or even definitively settle some of the arguments, but at least they should give us something to think about.

In Part 1, I will discuss the test range, test instrumentation and test procedures used for all the experiments. Part 2, which is included in this issue of *QEX*, discusses an earlier and apparently overlooked prediction from NEC,

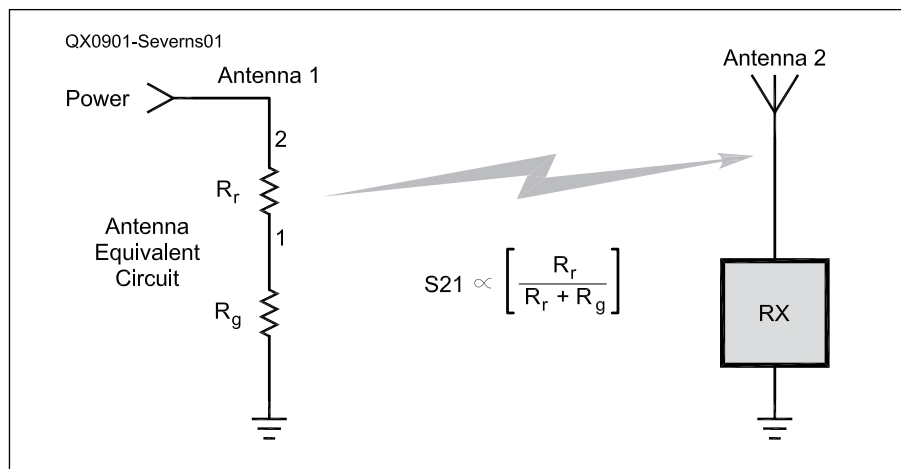


Figure 1—This drawing illustrates the traditional measurement scheme.

that in sparse (<10 radials) radial systems lying close to ground, there can be a substantial increase in ground loss when the radials are made much longer than $\frac{1}{8}$ wavelength. This is a case of more copper = more loss, which is not at all intuitive! Part 3 will compare verticals with a large number of ground surface radials to verticals with four elevated radials. This part will directly address the elevated radial controversy. Part 3 will also have comparisons between several different elevated radial configurations. Part 4 will

look at the effect of radial numbers on the characteristics of $\frac{1}{4}$ wavelength and several shorter loaded antennas. Part 5 will take a look at the problems of ground systems for multiband verticals, where a range of 7 to 30 MHz must be accommodated. Finally in Part 6, I will report on some experiments with a full size $\frac{1}{4}$ wavelength vertical on 160 m. In addition, because this series will take many months to be published, there will be lots of time for feedback. I plan to include some of this in Part 6.

Test Setup

The physical layout of the test range, the instrumentation employed and the test procedures were all key elements in obtaining reliable results. The following discussion provides descriptions of these elements which remained essentially constant for the experiments. The majority of measurements were done at 7.2 MHz although there was some work at 160, 30, 20, 17, 15 and 10 meters. The information given here is intended to provide information common to all the experiments.

Test Concept

The traditional test procedure for these kinds of measurements is well known. As shown in Figure 1, a test antenna is excited with a known power, and the resulting signal is measured at a remote point. A change is then made in the test antenna and the measurement is repeated. The difference between the two measurements is a measure of the effect of the change in the antenna and/or ground system on performance. The signal transmission to antenna 2 from the excitation of antenna 1 (S21) will be proportional to the radiation efficiency of the antenna. In other words, $S_{21} \sim \text{input power} \times R_r / (R_r + R_g)$ where R_r is the radiation resistance and R_g is the ground loss. For our purposes we can assume that losses due to conductors are small. Both R_r and R_g will vary as we change the ground system but the final goal is to see the effect on the transmitted signal.¹

The standard way to make these measurements is to use a transmitter combined with forward and reflected power meters to excite the test antenna (antenna 1) with a known power. A calibrated receiver is connected to a remote receiving antenna (antenna 2) to measure the resulting signal. In my initial tests I used both an HP3586C and an HP3585A spectrum analyzer for the receiver. I wished to measure the performance differences between configurations to within 0.1 dB if possible, and these instruments were capable of that. However, the limiting factor turned out to be my ability to measure the excitation power; 0.1 dB corresponds to about 2%. To make repeatable measurements to 0.1 dB you would need to measure power to better than 1%.

To get around that problem I decided to use the instrumentation scheme illustrated in Figure 2. I chose to make the measurements with a vector network analyzer (VNA) in the transmission mode (S21 is the response at port 2 due to the excitation at port 1). The transmission path was from the VNA output port, out to the test antenna via a transmission line, from there to the receive antenna and back to the VNA input port via

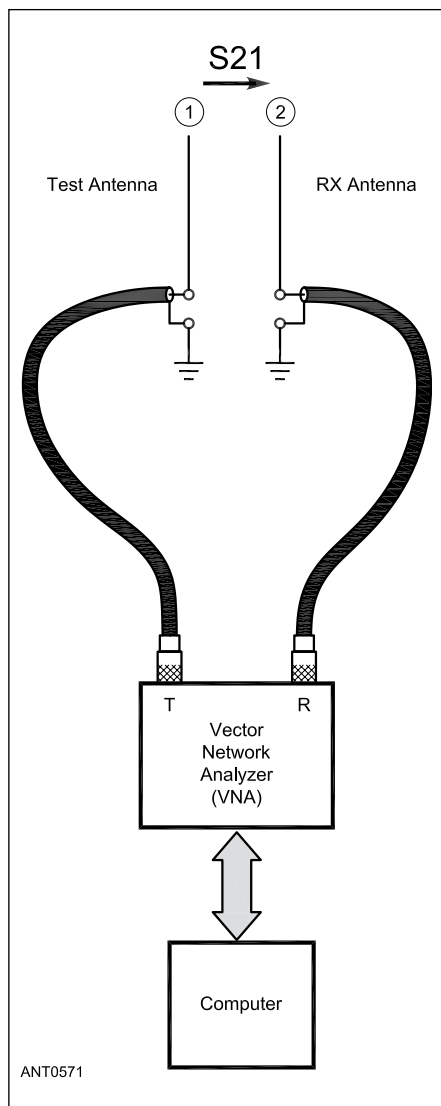


Figure 2 — This diagram shows the vector network analyzer approach for measuring antenna performance.



Figure 3— A view of the test antenna area and test equipment shelter. The receiving antenna is at the far end of the pasture.

another transmission line.

Amplitude measurements with a professional VNA are typically displayed to 0.001 dB, but of course nothing else in the system is stable to that level. In practice I found that measurements made over a short period of time (2-3 hours) were repeatable to within 0.05 dB. That is more than adequate for these experiments. A weakness of this measurement method is that as the separation between the test antenna and the receiving antenna is increased, the attenuation around the transmission loop becomes quite large, -40 to -60 dB. For instrumentation and a physical setup with a noise floor and stray coupling below -110 dBm, this is acceptable but it did limit the separation distance on 40 m to about 2.25 wavelengths for the particular receiving antenna employed. This is in the far field but not by much. Another limitation was that ± 0.05 dB repeatability was possible only when the antenna under test and the receive antennas were actually stable to that level. This usually meant that measurements had to be made in early morning when the test range was in the shade or late in the day when things had reached thermal equilibrium. It was very easy to detect a cloud passing over by the small changes due to temperature changes in the antennas. I could readily detect the effect of the wind on the vertical, causing it to move slightly. In the end the A-B comparison measurements were probably within a few tenths of a dB but only when I carefully attended to all the details.

This brings us to an important point. The purpose of the experiments was to determine the effect of different ground system arrangements from their effect on S21. All the measurements were relative A-B comparisons. In other words, they were comparisons between two different configurations. There was no

¹Notes appear on page 25.



Figure 4 — This photo shows a typical test antenna and center post support.

attempt to measure absolute signal strengths or radiation patterns. The separation distance between the test antenna and the receiving antenna was sufficient to place the receiving antenna outside the reactive near field but the groundwave was still significant. This was not a problem for the type of measurements being made. The presence of a metal pump house and a travel trailer, both of which are small in terms of a wavelength might have had an impact on pattern measurements but should not have affected the type of A-B measurements being made in this series of experiments.

Physical Arrangement

The test range was set up in a field as shown in Figure 3, with an area for the test antennas (including ground systems), a remote receiving antenna (in the far distance) and a small travel trailer to provide shelter for the instrumentation.

The eight poles, in an 80 foot diameter circle around the test antenna, were used to support elevated radials as needed. When more than eight elevated radials were needed, a ½ inch Dacron line was stretched around the posts at the desired height and tightened with a turn-buckle. Each post has a backstay to a buried deadman anchor so the radials could be well tensioned. Radial heights on each post were located using a laser level to keep the radial fan flat around the circle.

In the center of the circle there is a support post (PVC pipe) as shown in Figure 4, with Dacron support lines attached to the top. This post is intended to hold the antenna under test and allow it to move up and down to vary the height for elevated radial tests. An example



Figure 5 — Here is the test antenna base at ground level, with 64 radials.



Figure 6 — The base plate is in position for elevated radials.

of the base plate at ground level with 64 radials attached is shown in Figure 5.

The base plate is isolated from ground but there are three ground stakes (4 foot copper-clad steel rods) close to the plate for those tests where grounding is desired. The ground stakes have short pig-tail leads to connect to the base plate when desired.

Figure 6 shows an example of the base plate positioned for elevated radial tests. The base plate, the radials and the entire test antenna are elevated by sliding them along the support pipe. This arrangement made it very easy to change the height of the radials in small increments up to 4½ feet above

ground. The radials lying on the ground in Figure 6 were *not* present during elevated radial tests!

As shown in Figures 5 and 6, a coaxial common mode choke (balun) was used to isolate the transmission line from the test antenna. This was done for all measurements whether or not ground stakes were engaged. The choke has an impedance of >3 kΩ at 7.2 MHz. For those tests in which the SteppIR vertical was employed, the balun that comes with that antenna was used in lieu of the choke shown in the photos.

The receiving antenna was a 3-turn diamond loop with a diagonal dimension of

24 inches, as shown in Figure 7. The loop was resonant at 8.2 MHz. This loop was installed at the top of a 40 foot mast, as shown in Figure 8.

The distance from the base of the test antenna to the receiving loop is a little over 300 feet, about $2\frac{1}{4}$ wavelengths at 7.2 MHz. The elevation angle from the base of the test vertical is about 8° .

The coax from the VNA output port to the base of the test antenna was $\frac{1}{2}$ inch Andrews Heliax with N connectors. The coax from the receiving antenna back to the VNA was LMR400. Low loss coax was used because it provided better shield attenuation to reduce coupling and in the case of the heliax running out to the test antenna, the very low loss removed the need for an additional correction



Figure 7 — This photo shows the loop receiving antenna.



Figure 8 — Here is the receiving antenna atop a 40 foot mast. N7MQ assisting!

factor for the change in cable loss with variations in SWR.

Test Instrumentation

Feed point impedance, transmission gain (S21) and radial current measurements were all made using a VNA. Two analyzers were available: an HP3577A with an HP35677A S-parameter test box and an N2PK analyzer with dual fast detectors. Figures 9 and 10 are photos of these instruments.

Note the organic automatic heating unit

on top! Critical for maximum accuracy! The common mode choke in the photo is undergoing characterization for transmission loss and series impedance at 7.2 MHz. It turned out however, that the impedance of the choke was much greater than the $50\ \Omega$ reference impedance of the VNA. Above about $2\ \text{k}\Omega$ even an HP VNA becomes inaccurate for a direct measurement. For choke measurements, I used an HP4815 analyzer, which is well suited for high-impedance measurements.

After careful comparisons between the HP and N2PK VNAs, the N2PK was selected for

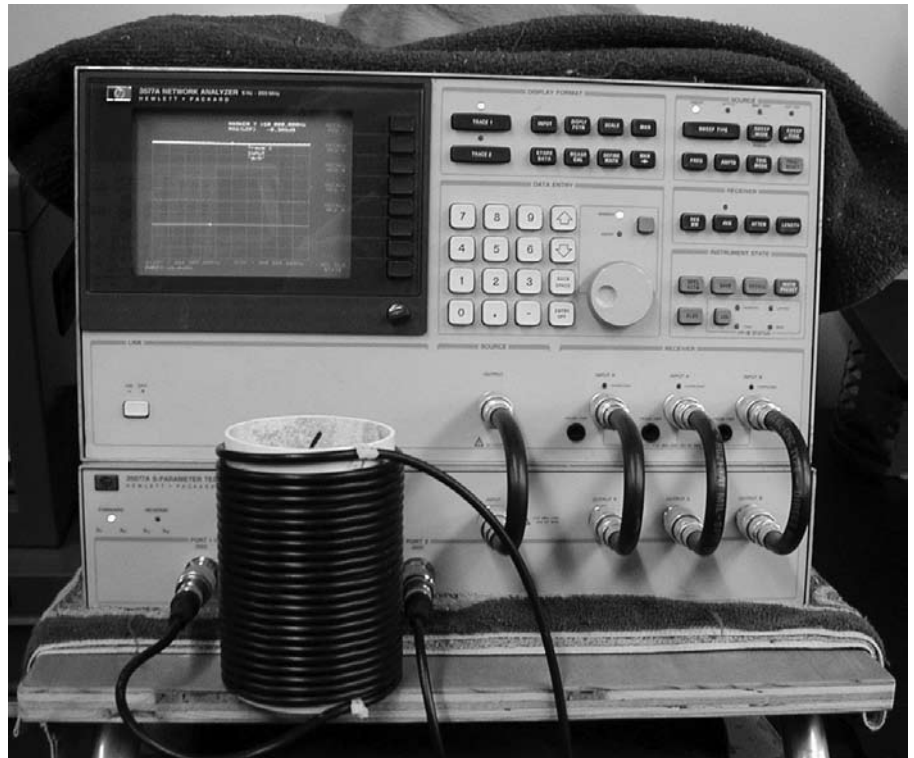


Figure 9 — HP3577A with an HP35677A S-parameter test box.



Figure 10 — Here is my test bench, showing the N2PK VNA with the associated laptop computer and HP calibration loads.

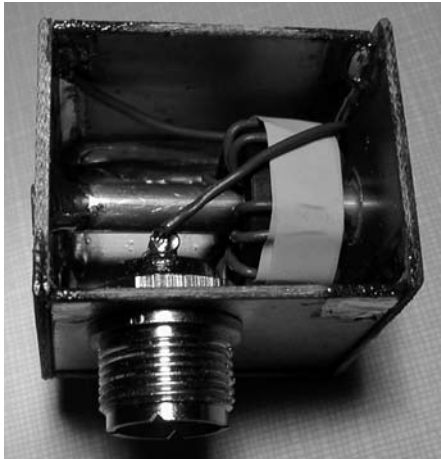


Figure 11 — This photo shows a typical shielded current transformer.

most of the measurements because its performance was very close to the HP and had the advantage of direct readout to a computer, which made data reduction much easier. The N2PK VNA was also much lighter than the HP (70+ pounds!) and much more suitable for field measurements.

On several occasions it was necessary to measure the current division ratios between the radials and in some cases, the relative current distribution along a radial. To make these measurements a set of shielded current transformers, like the one shown in Figure 11 were used.

To make a current measurement, a radial wire was passed through the current transformer, as shown in Figure 12. Current transformers were placed in the same location simultaneously on all the radials during a measurement. The transformer being used to sense current was terminated in 50 Ω by the instrumentation, so all of the dormant current transformers were also terminated in 50 Ω . This was done to compensate for any interaction introduced by the current transformer. At the very least, the effect of the current transformer would be the same on all radials. The active current transformer was isolated with a choke as shown in Figure 12.

Even with this degree of care, the current measurements were still a bit tricky because of the residual interaction between the cable from the current transformer and nearby radials. In some cases I actually used four identical cables in a symmetrical layout to try to minimize imbalance due to this interaction. I believe the resulting measurements were reasonable and useful but not especially precise!

The relative value of the current was determined by using the VNA in the transmission mode, measuring S21 for the loop from the VNA output port to the base of the antenna, out along the radial to the current transformer and back to the VNA input port. This was a convenient way to measure the

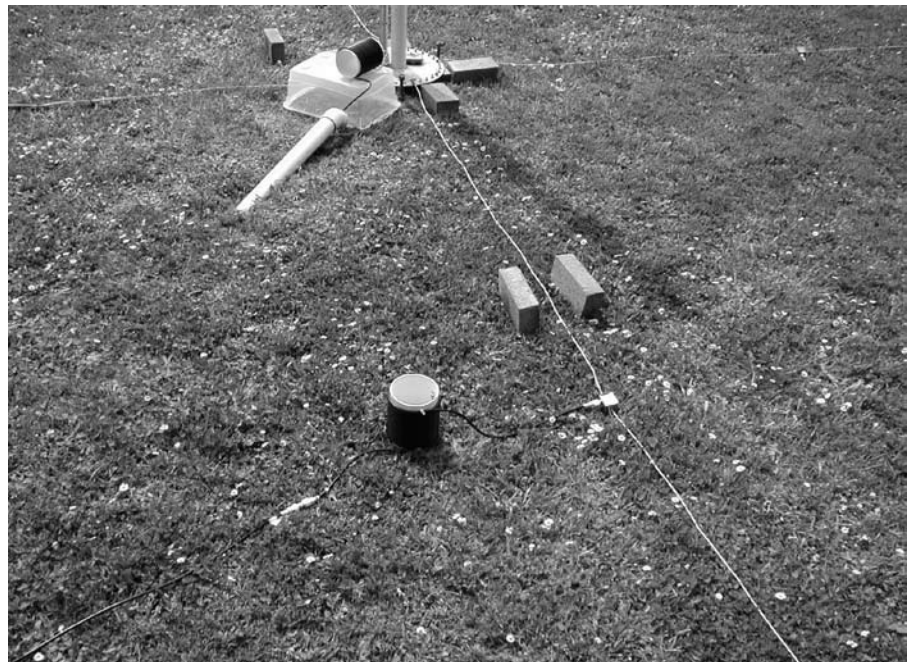


Figure 12 — Here is the test setup for a typical radial current measurement.

current division between radials and the relative current distribution along a radial.

Comments on test procedures

A good physical setup and professional instrumentation are a very good start, but to obtain reliable data great care must be exercised in using and calibrating this equipment. For feed point impedance measurements, at the beginning and end of every test run an OSL (open, short, reference load) calibration was performed with the calibration plane at the test antenna feed point. At the beginning and end of each test run a transmission calibration was also performed.

In addition, before beginning a series of measurements a measurement of stray coupling and possible interference was performed. The procedure was to disconnect the feed line from the base of the test antenna, terminate the feed line with a 50 Ω load and then measure the transmission gain of the entire system in this state. Throughout the series of experiments, this transmission level was never higher than -110 dBm and usually -115 dBm or lower, at 7.2 MHz. As a further check on results, most experiments were run several times to verify consistency and repeatability. All of this was very time consuming but absolutely necessary to assure the best possible measurements. I did not delude myself, however, into thinking the measurements were perfect and cannot be improved on. I do believe the results make sense, fit well with NEC modeling predictions, give useful insights into vertical antenna/ground system behavior, and potentially can be of practical help in optimizing a given antenna installation.

Acknowledgement

This experimental work was inspired by the earlier work of Jerry Seveck and Arch Doty.^{2, 3} Some of my experiments were a repeat of their earlier work with more advanced instrumentation. I would also like to thank Mark Perrin, N7MQ and Paul Thompson, W8IEB for the many hours of help they provided during the experiments. Without their help, I would still be out in the field taking measurements!

Notes

¹R. Severns, N6LF, "Radiation Resistance Variation With Radial System Design," Sep 2008. Available at: antennasbyn6lf.com.

²J. Seveck, W2FMI, *The Short Vertical Antenna and Ground Radial*, CQ Communications, Inc, 2003. Jerry's work also has appeared in a number of QST articles.

³A. Doty, K8CFU, "Improving Vertical Antenna Efficiency, A Study of Radial Wire Ground Systems," *CQ Magazine*, April 1984, pp 24-31. This article also has a very nice list of earlier references related to ground systems for verticals.

Rudy Severns, N6LF, was first licensed as WN7WAG in 1954 and has held an Extra class license since 1959. He is a consultant in the design of power electronics, magnetic components and power-conversion equipment. Rudy holds a BSE degree from the University of California at Los Angeles. He is the author of two books and over 80 technical papers. Rudy is an ARRL Life Member, and also an IEEE Fellow.



Experimental Determination of Ground System Performance for HF Verticals Part 2 Excessive Loss in Sparse Radial Screens

These experimental results may surprise you, and might turn "conventional wisdom" upside down.

In 1998, Jack Belrose, VE2CV, used *NEC* modeling to show the effect of resonant and non-resonant radials placed very close to the ground surface on the behavior of a $\frac{1}{4}$ wavelength vertical.¹ One of the observations in that article was that the use of a small number of $\frac{1}{4}$ wavelength (free space) radials, lying on the ground surface, could lead to much higher losses than expected, and that shortening the radials could actually reduce ground loss. This seems counter to more classical analyses which show that making radials too long may be a waste of wire but does no harm. The classic analysis, however, does not take into account the possibility of resonances in the radial screen that might amplify the radial current, increasing ground loss.

The purpose of this experiment was to see if a real antenna would actually demonstrate the predicted behavior, and validate the *NEC* predictions experimentally.

Description of the Experiment

The experiment was done in six parts spread over a three week period:

- 1) The antenna for part 1 was a telescoping

aluminum-tubing vertical, averaging 1 inch in diameter, with a fixed height of 34 feet. The test frequency was 7.2 MHz. I used four no. 18 insulated wire radials lying on the ground surface. All four radials were of equal length, which was varied from 33 feet down to 18 feet. The impedance at the feed point, the transmission gain (S21) and the current division ratios between the radials were measured and recorded. The antenna and radials were isolated from ground and the feed line with a common mode choke.

- 2) For part 2, part 1 was repeated, first isolated from ground and then with one or more ground stakes connected, to evaluate the effect of using ground stakes at the base of the antenna. Tests were also done without any radials, and with just 1, 2 or 3 ground stakes connected to the base plate.

- 3) Part 3 of the experiment was the same as part 1 except with 8 radials (no ground stakes).

- 4) For part 4, the antenna was changed from the fixed tubing vertical to a remotely adjustable SteppIR vertical. In parts 1, 2 and 3, the antenna height was kept constant at 34 feet, but in this part of the experiment the height was changed to re-resonate the antenna as the radial number and radial lengths were changed.

The test frequency was 7.2 MHz.

- 5) After completing the first four parts of the experiment it was clear that shortening the radials from the standard free space $\frac{1}{4}$ wavelength value did indeed improve the signal, at least in the case of 4 and 8 radials, so I wanted to see what the effect was for 16 and 32 radials. Trimming that many radials to gradually shorten them, however, was a bit more work and wasted wire than I was prepared for. Instead, I ran this part of the experiment first with 4, 8, 16 and 32, thirty-three foot radials, which I had on hand, and then with 4, 8, 16 and 32, twenty-one foot radials, which were also on hand. This gave me two data points for each number of radials. Again, the test frequency was 7.2 MHz, with measurements of S21 and feed-point impedance.

- 6) Part 6 of the experiment was a check to see if the same kind of improvement would be seen at 30, 20 and 15 m by shortening the radials from $\frac{1}{4}$ wavelength (free space). This part of the experiment was not nearly as thorough as the first five parts but did confirm that the same basic behavior was present at the higher frequencies as that seen on 40 m. The test frequencies were 10.120 MHz, 14.200 MHz and 21.200 MHz.

¹Notes appear on page 52.

Experimental Results

Part 1

Figure 1 shows the variation in $|S_{21}|$ (magnitude of the transmission gain) as a function of radial length. The amplitude scale is normalized to 0 dB for a radial length of 33 feet, which is approximately a $\frac{1}{4}$ wavelength in free space at 7.2 MHz. The Y-axis shows the improvement in dB as the radials are shortened.

The improvement is quite large, about 2.8 dB, which would have a noticeable effect on signal strength. In Belrose's paper the improvement was about 3.5 dB but that was for average soil. My average ground characteristics are approximately $\sigma = 0.015$ S/m and $\epsilon_r = 30$, which is quite a bit better than average ground. These values were derived from ground probe measurements.² One would expect more improvement for poorer soil.

An earlier experiment in which the current distribution on a 33 foot radial, at 7.2 MHz, was measured, gave the results shown in Figure 2.

A quick check was made during the present experiment, and the current distribution appeared to be essentially the same. From the current distribution we can see that the radial in Figure 2 is resonant well below 7.2 MHz. To move the current maxima back to the base of the vertical we would have to reduce the radial length by about 10 feet. Looking back at Figure 1, we see that we are very close to the maximum $|S_{21}|$ when the length has been reduced by 10 feet to 23 feet. What appears to be happening is that we are tuning the radials to resonance (or at least close to it) at 7.2 MHz to compensate for the loading effect of the soil in close proximity to the radial wire.

The division of current between the radials was measured for 18 foot and 33 foot

Table 1

Current Division Between Radials Normalized to 1 A of Total Base Current.

Radial Number	I_n , 33-Foot Radials (A)	I_n , 18-Foot Radials (A)
1	0.24	0.26
2	0.24	0.25
3	0.25	0.25
4	0.27	0.24

Table 2

Measured Feed Point Impedances

Radial length (ft)	Feed Point Impedance (Ω)
33	$135 + j28$
30	$108 + j55$
27	$83 + j51$
24	$67 + j37$
21	$60 + j22$
18	$57 + j8$

lengths. Table 1 shows the results. The current division was quite uniform and the differences too small to have significant effect on the observed gain changes.

The variation of feed-point impedance as the radial lengths were shortened (with the vertical height constant at 34 feet) is shown in Table 2.

Parts 2 and 3

Part 1 was done during a week of heavy rain. Parts 2 and 3 were performed 8 days after part 1, when the soil had drained and dried out significantly so the ground characteristics may have changed somewhat.

The next step in the experiment was to expand the radial count from 4 to 8 radials and also to investigate the effect of using grounding stakes (4 foot copper clad steel

rods) connected at the base of the antenna. Measurements with 4 and 8 radials were repeated in each run. This run was with a fixed height for the vertical (34 feet). The results are shown in Figure 3.

At all lengths, 8 radials are an improvement over 4. With 8 radials, the amount of improvement with radial shortening is smaller but still useful. We can also see that adding a ground stake in the case of 4 radials also makes a substantial improvement but we should keep in mind that my soil would be classified as "very good" so we would expect ground stakes to be more effective than they would be in poorer soil.

The results for the case of no radials and 1, 2 or 3 ground stakes, normalized to the cases of four 33 foot radials and four 21 foot radials, with no ground stakes, are given in Table 3. Vertical height was constant at 34 feet.

Part 4

In part 4 I changed to the SteppIR vertical and adjusted the height to re-resonate the vertical for each radial length. The results are shown in Figure 4, which are very similar to the results for constant height given in Figure 3. No ground stakes were employed.

Part 5

From the earlier test results, I could see that the improvement due to radial shortening decreased as the number of radials increased.

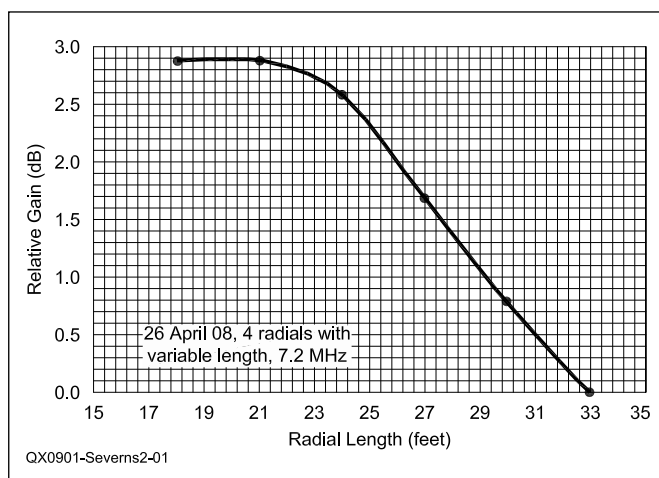


Figure 1 — This graph shows the improvement in $|S_{21}|$ as the radials were shortened. There were four radials lying on the ground surface.

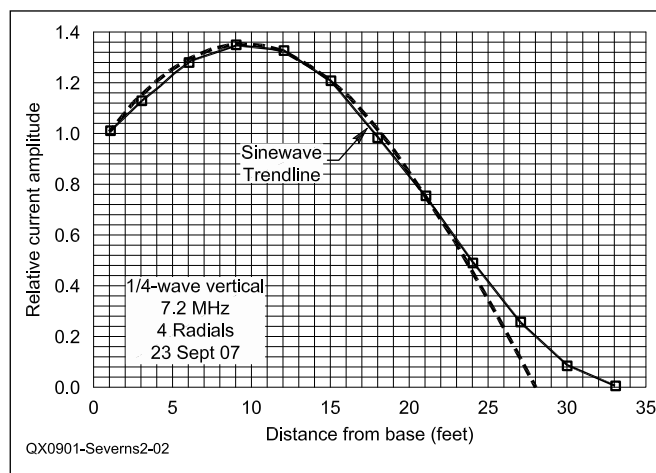


Figure 2 — This graph shows the relative current amplitude along a radial.

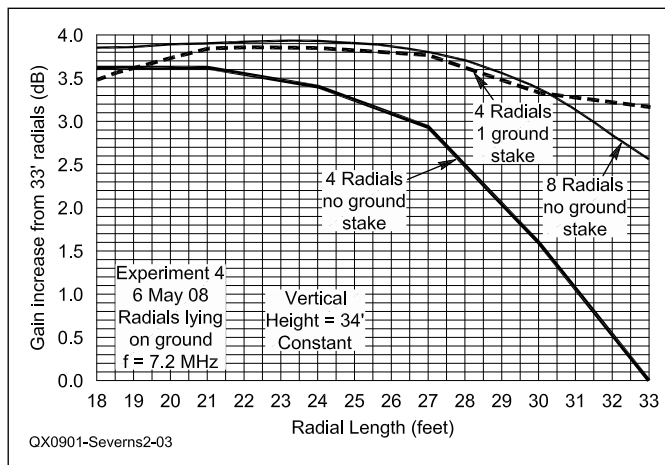


Figure 3 — This graph shows the change in |S21| with radial length. The vertical antenna height was a constant 34 feet.

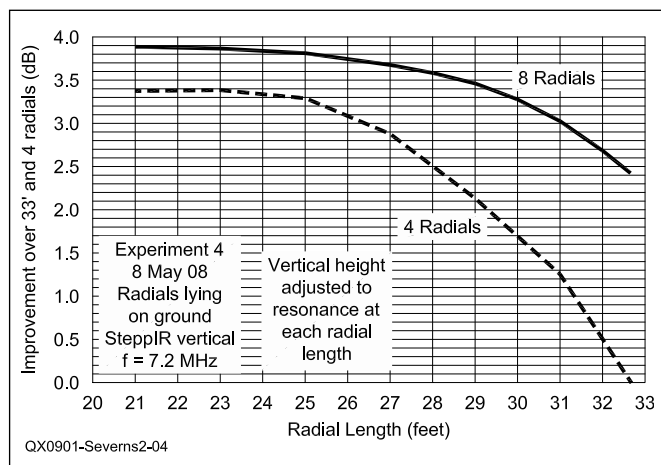


Figure 4 — This graph shows the change in |S21| with radial length. I adjusted the SteppIR antenna height to resonance for each radial length.

Table 3

Test Results for no Radials and 1, 2 or 3 Stakes, Compared to 4 Radials with no Ground Stakes.

Number of Stakes	Feed Point Z (Ω)	Compared to Four 33-Foot Radials, No Ground Stakes (dB)	Compared to Four 21-Foot Radials No Ground Stakes (dB)
1	$77 + j 40$	2.67	-0.95
2	$69 + j 30$	3.09	-0.53
3	$66 + j 26$	3.25	-0.37

Table 4

Results for 4, 8, 16 and 32 Radials, with Lengths of 33 Feet and 21 feet.

Number	33-Foot Radials Feed Point Impedance (Ω)	21-Foot Radials Feed Point Impedance (Ω)	33-Foot Radials S21 Relative to Four 33-Foot Radials (dB)	21-Foot Radials S21 Relative to Four 33-Foot Radials (dB)	Delta Gain Change (dB)
4	89.8	52.5	0	3.08	+3.08
8	51.8	45.6	2.26	3.68	+1.42
16	40.5	42.8	3.76	3.95	+0.19
32	37.7	41.6	4.16	4.04	-0.12

In this part of the experiment the number of radials was extended to include 16 and 32 radials to quantify that difference. The test was conducted with sets of 4, 8, 16 and 32 thirty-three foot radials, and then repeated with the same numbers of 21-foot radials. The SteppIR antenna was used, and its height was adjusted to re-resonate as the radials were altered. The results are tabulated in Table 4. These measurements were made several days after those used in Figure 4, so there are some differences because of small changes in the ground characteristics, radial layout, and other conditions. These day-to-day variations are a major reason for repeating some parts of earlier experiments multiple times and trying to do a complete experiment in a short period of time (a couple of hours).

It should be noted that a ground system consisting of only four radials is really flaky.

Measurements vary significantly with small variations in radial layout, changes in soil moisture, placement of the feed line relative to the radials, and so on. Shortening the radials does seem to reduce this sensitivity, but even so, a four radial system should only be an emergency measure.

As expected, as the number of radials is increased the change due to radial shortening gets much smaller. Over the very good ground on which these measurements were made, shortening the radials gave only a modest advantage when more than 8 radials were used. Over poorer soils, however, radial shortening with 16 radials might be worth doing. The lower value for feed point impedance (Z_f) with 33-foot radials is at least in part due to the shorter height needed to resonate. For 21-foot radials the height had to be increased to re-resonate the antenna.

It is interesting to note that with 32 radials, the 33-foot radials were actually slightly better (0.12 dB) than 21-foot radials. Quite probably there was some optimum length in-between that may have been slightly higher than either, but that is not likely to be very large and I decided it wasn't worth the trouble to cut up a set of 32 radials to find out. The important point is that the changes in gain, input impedance and height variation to re-resonate all get much smaller when more radials are used. I would think that with 32 or more radials you wouldn't worry about resonances in the radial screen. The problem is only important when fewer than 16 radials are deployed.

Table 5 shows the antenna height (h) in inches. This is the reading from the control box. The actual height is about 12 inches longer due to the height above ground of the

Table 5
Indicated Height of the Vertical.

Number of Radials	33-Foot Radials <i>h</i> (inches)	21-Foot Radials <i>h</i> (inches)
4	357	381
8	366	382
16	374	382
32	377	382

reel and the lengths of connecting wires, plus the length of radials from the reel box to ground surface. The columns for *h* do, however, give an idea of the change in height. In the case of 33-foot radials the change is quite large (20 inches) between 4 and 32 radials. On the other hand with 21-foot radials the change in *h* with radial number is very small, fractions of an inch. The values in the Table are rounded off to the nearest inch.

Part 6

In the final part of this experiment the effect of radial shortening on 30, 20 and 15 m was examined. This was really just a quick look using radials left over from the earlier parts of the experiment, cut down from them rather than making up a new set of ¼ wavelength (free space) radials for each band. *In all three cases 8 radials were used.* The test frequencies were: 10.120 MHz, 14.200 MHz and 21.200 MHz. The corresponding free space ¼ wavelengths would have been, 24.3 feet, 17.3 feet and 11.6 feet respectively. The results are shown in Tables 6, 7 and 8. The value for $|S_{21}|$ is the actual measurement.

One oddity in this data was that the best radial length on both 30 and 20 m was the same, about 15 feet. There is some dispersion (variation with frequency) in the soil characteristics but I don't think that's a full explanation. In all cases the optimum length was well short of the free space ¼ wavelength. I think this part of the experiment needs to be rerun cutting down from full length radials. This will be done at some future time.

NEC Modeling

At this point it was clear that Belrose's original work was basically confirmed experimentally, but I was curious to see how closely this data could be replicated using *NEC4-D* modeling software (*EZNEC Pro* + *MultiNEC*). The first trial model employed 4 radials with lengths from 6.4 m (21 feet) to 10 m (33 feet). The wire table for this model is given in Table 9. The radials were placed 5 mm above 0.01/14 soil. The test frequency was 7.2 MHz and the vertical height was adjusted to maintain resonance as the radial number was changed.

We can compare the maximum gain data against the experimental data for 4 radials (from Figure 4) as shown in Figure 5.

The match in gain data is very good, as was the current distribution on the radials. The impedance data was also close. We can also see what *NEC* predicts about the current distribution on a radial as we change the length. Figure 6 shows the current distribution on a 33-foot radial for *NEC* model 1.

Figure 6 looks very similar to the experimental measurement shown in Figure 2. When we shorten the radials to 21 feet, we get the current distribution shown in Figure 7. This is very close to resonance.

The match in gain and current distribution, however, is really too good to be believed. First of all, this is not an exact model of the real antenna. The vertical uses a strip of beryllium-copper, not a no. 12 wire, and I believe my ground characteristic is better than the 0.01/14 used in the model. Models with wires very close to the ground sur-

Table 6
30 m, ¼ Wavelength Free Space = 24.3 Feet.

Radial Length (ft)	$Z_i (\Omega)$	$ S_{21} $ (dB)	<i>h</i> (in)
21	44.4	-62.31	260
20	41.6	-61.12	261
18	41.0	-61.84	264
16	42.6	-61.78	267

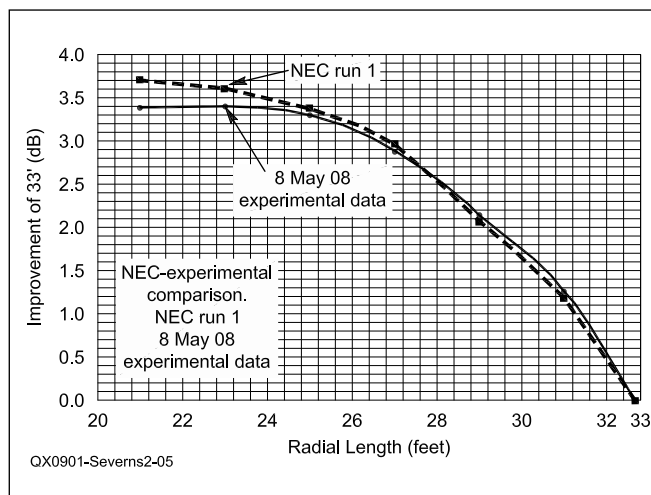


Figure 5 — Here is a comparison between *NEC* modeling run 1 and the experimental data using 4 radials taken on May 8, 2008.

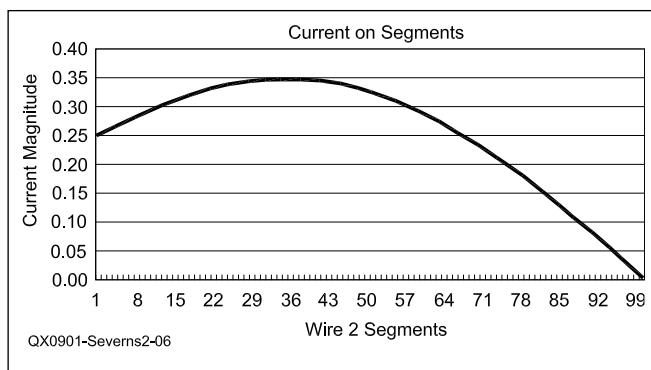


Figure 6 — This graph shows the current distribution on a 33 foot radial (*NEC* model).

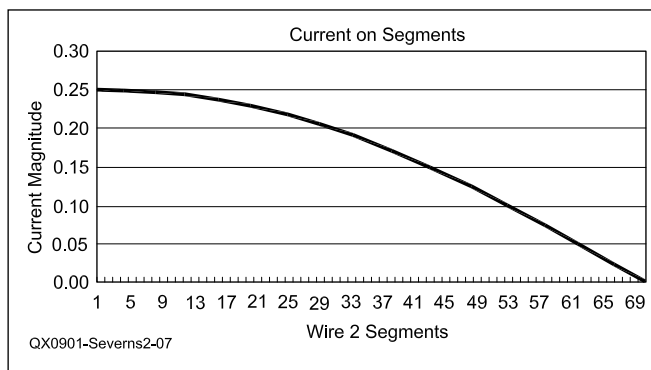


Figure 7 — Here is the current distribution on a 21 foot radial (*NEC* model).

Table 7**20 m, ¼ Wavelength Free Space = 17.3 Feet.**

Radial Length [ft]	Z_i (Ω)	$ S_{21} $ (dB)	h (in)
16	37.8	-62.03	178
15	36.0	-61.84	179
14	35.0	-61.91	181

Table 8**15 m, ¼ Wavelength Free Space = 11.6 Feet.**

Radial Length [ft]	Z_i (Ω)	$ S_{21} $ (dB)	h (in)
9	27.3	-60.34	60
8	30.0	-60.29	60
7	34.3	-60.11	60
6	41.0	-60.46	60

Table 9**Model Wire Table**

End 1 X (m)	Y (m)	Z (m)	End 2 X (m)	Y (m)	Z (m)	Diameter (mm or #)	Segs (359)	Show Lengths in Wire	• m Length	o wl Seg Len
40 m gp 4 rad A										
0.000	0.000	0.005	0.000	0.000	10.306	#12	103	W1	10.301	0.100
0.000	0.000	0.005	6.400	0.000	0.005	#12	64	W2	6.400	0.100
0.000	0.000	0.005	0.000	6.400	0.005	#12	64	W3	6.400	0.100
0.000	0.000	0.005	-6.400	0.000	0.005	#12	64			
0.000	0.000	0.005	0.000	-6.400	0.005	#12	64			

Table 10 **Z_i and Peak Gain**

Freq (MHz)	L	M	R at Src1	X at Src1	SWR(50 Ω)	Max Gain
7.200	9.056	10	83.15	0.03	1.663	-4.41
7.200	9.275	9.45	65.72	0.01	1.314	-3.22
7.200	9.535	8.84	54.59	0.00	1.092	-2.12
7.200	9.757	8.23	49.83	-0.01	1.003	-1.45
7.200	9.955	7.62	48.23	-0.02	1.037	-1.04
7.200	10.136	7.01	48.48	0.01	1.031	-0.81
7.200	10.306	6.4	49.91	-0.02	1.002	-0.70

Where L is the height of the vertical in meters and M is the length of the radials in meters.

face are very sensitive to small changes in the model and wire segmentation. A change in height as small as 1 mm when the wires are at 5 mm above ground, makes a very substantial change in the results. By diddling the model, I can get the kind of match shown in Figure 5, but when I go the other way and attempt to use the model to predict the behavior of the real antenna, the results could be way off. When it comes to wires very close to ground — distances comparable to the wire diameter — *NEC* replicates the general behavior but you do not know enough of the details of the real antenna and it's immediate environment to expect exact quantitative results from the model.

In addition, the characteristics of real soil vary widely even at a fixed location: vertically, horizontally and over time. The soil will very likely have grass (weeds?) over it, which varies in length and water content during the year. We will seldom have more than a general idea what our ground characteristics are even with ground probe measurements.

We will also not really know the height above ground to a fraction of mm! The radials will be buried somewhere in the grass, so who knows what the effective height really is.

Final comments

The effect that showed up initially in Belrose's article and in later *NEC* modeling appears to be real. I think it is clear that in a sparse radial system lying directly on the ground surface, it is possible to incur substantial additional ground losses over what we might expect. The prediction from *NEC* modeling of this effect appears to be confirmed, at least qualitatively. I have been able to reproduce it experimentally multiple times, on multiple bands, with different antennas.

While *NEC* predicts the effect, you can't rely on *NEC* modeling for exact predictions. You will have to do final adjustment in the field. This is not a general indictment of *NEC*. When the antenna has not been right

down next to the ground surface, I have found *NEC* predictions to be very good when I went out and built the actual antenna.

We have a couple of ways to attack the problem of radial resonance and excess ground loss: first, cut the radials to be near resonance while lying on the ground. That works if you have the instrumentation, but is hardly a practical approach in general. The second and much more practical approach is to use at least 16, or better yet, 32 radials. As I pointed out earlier, ground systems using only a few radials are a poor idea for many reasons.

Notes

¹J. Belrose, VE2CV, "Elevated Radial Wire Systems For Vertically Polarized Ground-Plane Type Antennas, part 1 — Monopoles," *Communications Quarterly*, Winter 1998, pp 29-40.

²R. Severns, N6LF, "Measurement of Soil Electrical Parameters at HF," ARRL, QEX, Nov/Dec 2006, pp 3-9.



Experimental Determination of Ground System Performance for HF Verticals

Part 3

Comparisons Between Ground Surface and Elevated Radials

Experimental results from another of the author's antenna experiments.

Over the years there has been a great deal of discussion regarding the relative merits of a vertical antenna with a few elevated radials versus one with a large number of radials either lying on the ground or buried just below the surface. *NEC* modeling predicts that as few as four radials, a few feet above ground, will provide as efficient a ground system as a large number of on-ground radials. Whether this prediction is valid is a matter of some dispute. Resolving this issue is important for amateurs using HF vertical antennas.

The first segment of the experiment was a comparison of the performance of a $\frac{1}{4}$ -wavelength vertical antenna with a large number of ground surface radials (64) to one with only four elevated radials. From the results in segment one it appeared that elevated radial systems for HF verticals have some merit. But there are a number of different ways to implement an elevated radial system. The purpose of the second segment of the experiment was to evaluate the relative performance of several different elevated radial schemes.

Segment One

All measurements were made at 7.2 MHz using a 33.5 foot tubular aluminum vertical antenna. The experiment began with sixty four, 33 foot no. 18 AWG insulated wire radials lying on the ground surface.

The antenna was insulated from ground and used a common mode choke (balun) in the feed line. With a height of 33.5 feet and 64 radials, the vertical was close to resonance at 7.2 MHz.

During the experiment, $|S_{21}|$ (magnitude of the transmission gain, see Part I of this series)¹ and the input impedance at the feed point (Z_i) were measured and recorded as the radial system was changed. The experiment began with 64 radials lying on the ground

surface. Without changing the height of the vertical, $|S_{21}|$ and Z_i were measured as the radial number was reduced in the following sequence: 64, 32, 16, 8, 4. The next step was to make a series of measurements, beginning with the four radials on the ground and then elevating the radials and the base of the vertical to 6 inches, 12 inches and finally 48 inches. At the 48 inch height, a measurement of the current division between the radials was made.

This entire sequence was repeated three times on different days. The results did not change significantly between test runs.

¹Notes appear on page 32.

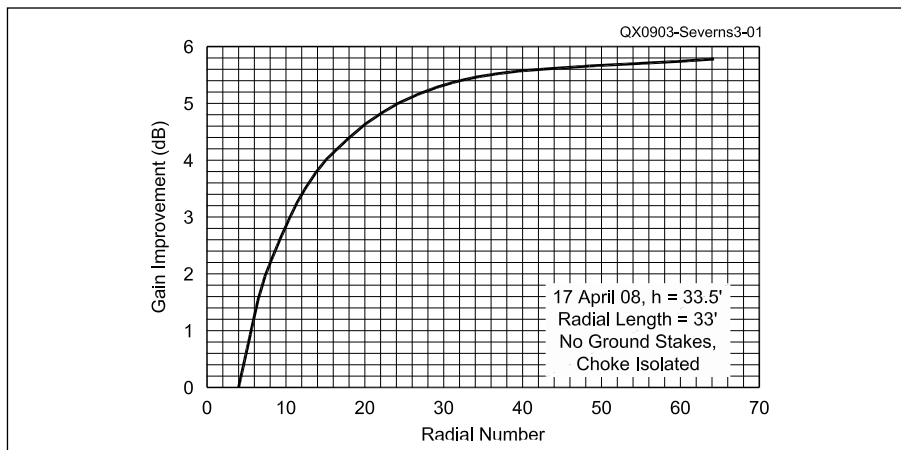


Figure 1 — $|S_{21}|$ as a function of radial number. All radials are lying on the ground surface.

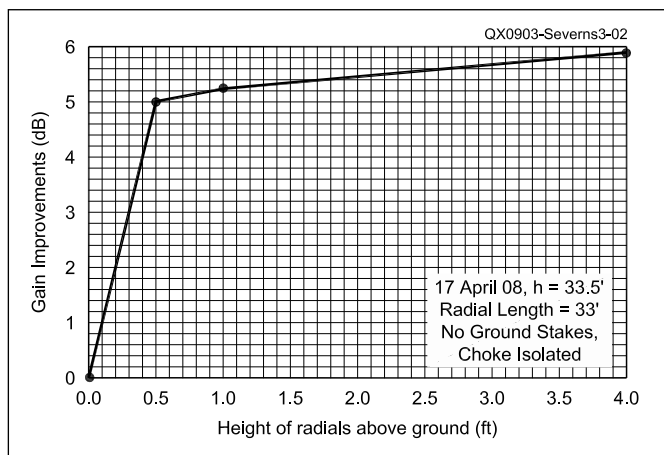


Figure 2 — $|S_{21}|$ with 4 radials and the antenna base at different heights.

Experimental Results

The observed variations in $|S_{21}|$ as radial number and height were changed are shown in Figures 1 and 2. In the graphs, $|S_{21}|$ has been normalized (0 dB) to the value for 4 radials lying on the ground surface, so that the graphs show the *improvement* in dB as either the radial height or number were increased.

From Figure 1, we see that with 64 radials lying on the ground surface $|S_{21}| = +5.8$ dB. From Figure 2, for four radials and the base of the antenna elevated 48 inches above ground, we see that $|S_{21}| = +5.9$ dB. The difference is only 0.1 dB. For any practical purpose, the two ground systems are equivalent, which is in accord with *NEC* predictions.

The large change in $|S_{21}|$ with radial number in Figure 1, which is predicted by *NEC*, is mostly the result of additional loss caused by resonances present in sparse radial screens. This effect was discussed in Part 2 of this series.²

The very large change between 0 inches and 6 inches in elevation shown in Figure 2 was also predicted by *NEC*. A typical prediction from *NEC* of peak gain versus radial height is shown in Figure 3.

The data line labeled “nonresonant radials” corresponds to constant length (33 feet) radials, which are not shortened to compensate for the effect of the soil characteristics on the radial resonant frequency. The other data line shows the effect of adjusting the length of the radials to re-resonate the antenna as the height above ground is altered.

Typical measured values for Z_i during the experiment are given in Table 1.

The measured current division between the radials, normalized to 1 A of total base current, is given in Table 2.

The radial current asymmetry was small

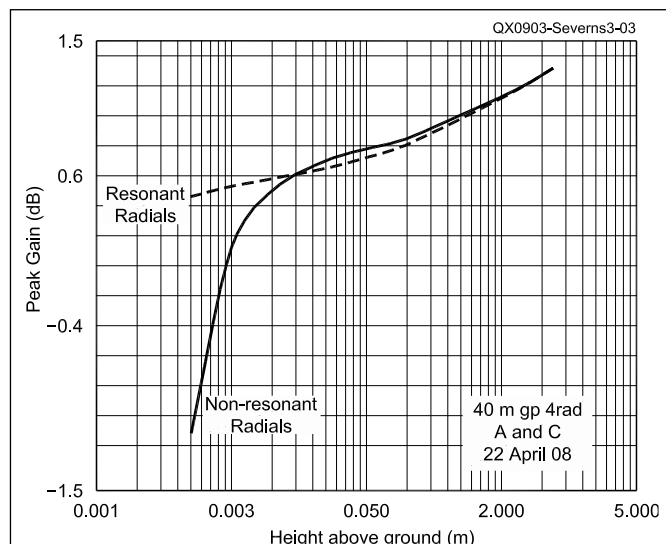


Figure 3— *NEC* prediction of peak gain versus radial height for 4 radials.

Table 1

Experimental Values for Feed Point Impedance.

Number of Radials	Radial Height (Inches)	$Z_i (\Omega)$
64	0	$39.7 - j1.2$
32	0	$42.9 + j2.1$
16	0	$56.1 + j6.2$
8	0	$85.5 + j8.0$
4	0	$137 + j14.9$
4	6	$43 + j6.4$
4	12	$40.6 + j0.08$
4	48	$34.8 - j9.7$

Table 2

Current Distribution in the Radials When Elevated to 48 Inches.

Radial Number	Relative Current (A)
1	0.235
2	0.271
3	0.247
4	0.247

Table 3

Gain Comparisons With One and Four Radials.

Radial Number (dB)	Azimuth (Degrees)	Peak Gain (dBi)	Elevation (Degrees)	Delta from 4 Radial Case (dB)	Delta from 4 Radial Case
4	0	+1.15	21.4	0	X
4	0	-1.12	8	X	0
1	0	+0.38	22.8	-0.77	X
1	0	-2.04	8	X	-0.92
1	90	-0.36	22.8	-1.51	X
1	90	-2.79	8	X	-1.67
1	180	-2.19	19.8	-3.34	X
1	180	-4.59	8	X	-3.47

enough to not have any meaningful effect on |S21|. Earlier measurements on radial systems with 64 radials, lying on the ground surface, also showed little asymmetry in the current division.

Effect Of Radial Current Division Asymmetry

As shown by Weber, it is very common for the current division between the radials in an elevated radial system to be unequal, especially if there are only a few radials.³ This asymmetry can affect the radiation pattern, and may possibly explain some of the variation in earlier comparisons. For this reason, I was very careful to minimize that asymmetry.

To get worst case estimates of the effect of current asymmetry on the pattern, I did some NEC modeling. Two models, the first with four radials and the second with one radial, are shown in Figures 4 and 5.

Comparisons between the peak gain and the gain at 8° elevation are given in Table 3. I have shown the peak gain and its associated angle, and also the gain at 8°, which corresponds to the angle to the test range receive antenna. As Table 3 shows, that makes little difference in the magnitude of the pattern distortion.

The worst case signal reduction from the four-radial case is at the 180° azimuth, with one radial. If all the current were in the radial pointing away from the receive antenna, the signal strength would be a bit over -3 dB from the case where all four radials had the same current. I examined models with 1, 2, 3 and 4 radials, but the worst case is for a single radial. That is hardly surprising.

Segment 2

The “standard” elevated radial scheme has four or more radials elevated above ground by 4 feet to 10 feet, with the base of the vertical antenna also elevated so that the radial fan is essentially flat. For a variety of practical reasons, however, somewhat different radial configurations are often used and it is of some interest to see what effect these variations have on the performance of the antenna.

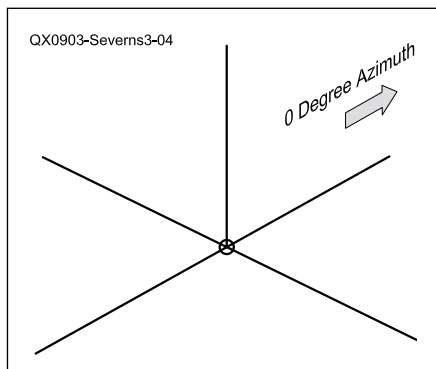


Figure 4 — Four elevated radials, 48 inches above 0.015/30 soil.

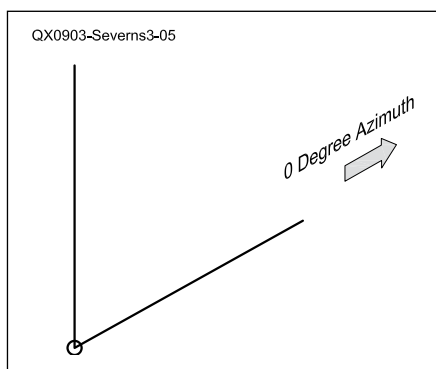


Figure 5 — One elevated radial, 48 inches above 0.015/30 soil.

Description of the Experiment

All the experimental runs were done with four 35 foot radials (except as noted), the length of the vertical set to 34 feet and a test frequency of 7.2 MHz. The antenna, including radials, was isolated from ground with a common mode choke (balun) in the feed line. Measurements of |S21| and Z_i were made for each test configuration.

The following configurations were tested:

- 1) Radials and antenna base elevated at 48 inches above ground.
- 2) The far end of the radials at 48 inches sloping down to the base at ground level.
- 3) A “gullwing” configuration as sug-

gested by Dean Straw, N6BV, and later extensively modeled by Al Christman, K3LC.⁴ The base was at ground level with the radials rising from the base at a 45° angle until they reached 48 inches above ground. The rest of the radials beyond this point were kept at 48 inches above ground from this point out to the far ends.

4) Radial lengths cut to 17.5 feet ($\approx \frac{1}{8}$ -wavelength). Radial and base height set to 48 inches. Antenna resonated with a 2.2 μ H inductor.

5) For reference purposes, a run was made with the radials lying on the ground surface and the antenna base at ground level. This was done as a check because segment one of this experiment had been done earlier and ground conditions at the site had changed. Also a slightly different radial length was used (35 feet versus 33.5 feet).

Experimental results

The experimental results are summarized in Table 4. The values for |S21| were normalized by setting the value for configuration 1 to 0 dB and the rest to the difference between them and configuration 1. A line of data from an earlier experiment has been added for comparison. (See Note 2.)

As a check, for configuration 1, the current division between the radials was measured. Those results are summarized in Table 5.

Comments on Segment Two

The most important observation is that radically changing the radial geometry does not seem to have a major impact on performance (|S21|).

Table 5

Measured current division between radials, normalized to 1A total base current.

Radial number	Normalized Current (A)
1	0.249
2	0.269
3	0.260
4	0.221

Table 4

Experimental Results

Configuration Number	S21 Normalized (dB)	Z_i (Ω)	Test Configuration
1	0	$39 + j6.3$	Base and 4 radials elevated at 48 inches
2	-0.47	$36 + j6.2$	Base at ground level, radials ends at 48 inches
3	-0.65	$29 - j11$	Gullwing, base at ground level radial ends at 48 inches
4	-0.36	$39 + j0.9$	Base and radials at 48 inches radial length = 17.5 feet 2.2 μ H inductor to resonate
5	-5.19	$132 + j22$	Base and radials on ground surface, four 35 foot radials
Earlier Experiment (See Part 2)	-1.79	$51 + j1$	Base and radials on ground surface, Four 21 Foot Radials

Cutting the radial lengths in half (configuration 4) and adding a small loading inductor reduced the gain by only -0.4 dB. The use of shorter radials has been suggested by Weber (see Note 3) and Moxon to either make the radial screen footprint smaller and/or reduce asymmetry in the current division between radials.⁵

I was surprised to see that the gain reduction for the gullwing configuration (configuration 3) was slightly worse than simply running the radials straight up to the far end (configuration 2). It may have something to do with the higher feed point impedance in configuration 2. In the case of the gullwing, the radials rise close to the vertical element, resulting in some cancellation between the vertical element and radial currents depressing the feed-point resistance. We see a similar effect in top-loaded antennas with sloping wires. From the standpoint of keeping the radials above head height for safety reasons, the gullwing is more attractive than just sloping up the radials.

It would seem that anything done to get the radial wires away from ground makes a great improvement as you can see from configuration 5, where the radials are lying directly on the ground surface. Even using shorter, resonant radials on the ground surface is not as effective as simply elevating the radials. Modeling and experimental work shows that you don't have to get very high to make a substantial improvement but greater heights are used for safety reasons to keep the radials above head height.

One thing missing from this experiment was the use of more than four radials. An earlier experiment which compared four elevated radials to eight in configuration 1, showed very little difference in |S21| (about + 0.2 dB). The advantage of more radials is not so much improved efficiency but rather reduced chances for radial current asymmetry and a lower Q, which can improve the SWR match bandwidth.

Summary

The experiments seem to show that a few elevated radials can work well as a replacement for a large number of ground radials. The experiments also show that alternate elevated radial geometries can work nearly as well as the "standard" and may have practical advantages.

Certainly this set of experiments does *not* completely resolve the debate regarding a large number of ground radials versus a few elevated radials, but it does lend some credence to the NEC modeling. To finally resolve these questions we need other experimenters to repeat these and/or similar experiments. We should also recognize that these experiments were done at a particular site,

which has good to very-good soil. Repeating the tests over other soils, particularly poor ones, would be of considerable interest. It is at least possible that larger differences between the ground surface and elevated radials might be seen.

Even if these tests and NEC modeling are in fact correct and a few elevated radials can, in principle, provide equivalent performance to a large number of ground radials, this does not mean we should dash out and convert all our ground systems to four elevated radials. Because of their much higher Q, elevated radial systems are subject to a number of ills. They are very sensitive to details of layout, soil characteristics, nearby conductors, coupling to feed lines, and other factors. Like ground radials, elevated radial systems work much better if the screen is not too sparse: in other words, try to use 12 or more radials. You will be much happier.

Notes

¹Rudy Severns, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 1," *QEX*, Jan/Feb 09, pp 21 - 25.

²Rudy Severns, N6LF, "Experimental Determination of Ground System Performance for HF Verticals, Part 2," *QEX*, Jan/Feb 09, pp 48 - 52.

³Dick Weber, K5IU, "Optimum Elevated Radial Vertical Antennas," *Communication Quarterly*, Spring 1997, pp 9 - 27.

⁴R. Dean Straw, N6BV, "Antennas Here Are Some Verticals On The Beach," *ARRL Antenna Compendium*, Vol 6, pp 216 - 225.

⁵L. Moxon, G6XN, "Ground Planes, Radial Systems and Asymmetric Dipoles," *ARRL Antenna Compendium* Vol 3, pp 19- 27.

Rudy Severns, N6LF, was first licensed as WN7WAG in 1954 and has held an Extra class license since 1959. He is a consultant in the design of power electronics, magnetic components and power-conversion equipment. Rudy holds a BSE degree from the University of California at Los Angeles. He is the author of two books and over 80 technical papers. Rudy is an ARRL Member, and also an IEEE Fellow.

QEX

Experimental Determination of Ground System Performance for HF Verticals

Part 4

How Many Radials Does My Vertical Really Need?

Experimental results to answer an often-asked question.

A frequently asked question is “How much of a ground system do I really need to make my vertical antenna work?” Usually, what’s wanted is an answer in the form of “This much ground system will improve your signal by X dB.” Another common question is “Does it matter if I lay the radials on the ground surface instead of burying them?” This is a practical consideration because it’s often much easier to lay out the radials on the surface and let them vanish into the grass.

These questions can be addressed analytically and with modeling, but for most of us that’s not very convincing. It’s much more satisfying to see actual field measurements on real antennas. In the past there has been professional work at MF broadcast frequencies and also the excellent work by Jerry Sevick, W2FMI, at HF.^{1,2} The problem with an experimental approach is the practical limit on the number of test examples: you can’t do all the possible variations! What’s needed are reliable field measurements that can be compared to calculations and/or modeling to see if there is reasonable correlation. If there is, we can use calculations or modeling for the wide variety of anten-

nas and soil characteristics we which we couldn’t test.

Some of the material that follows represents a redo of Sevick’s work with better instrumentation, but the material in this section, along with the other five parts of the series, goes well beyond Sevick’s work. The details of the test equipment and experimental setup were given in Part 1 of this series.³

Efficiency Limitations

The purpose of the ground system is to improve antenna efficiency so that less power is lost in the soil and more is radiated. Efficiency is the ratio of the power radiated to the total input power at the feed point. Of course what we want is to radiate all the input power (100% efficiency) and maximize our signal, but there are practical limits. We can represent the resistive part of the feed point impedance (R_s) by three series resistors as shown in Figure 1.

The input resistance at the feed point is $R_s = R_r + R_g + R_l$. We have to be a bit careful what we mean by “radiation resistance.” R_r is usually defined as the value of the resistance at a current maximum attributable to radiation. In a vertical antenna with a height of $\frac{1}{4} \lambda$ or less over perfect ground, this point is at the base of the antenna, which is the usual feed point. In real antennas with

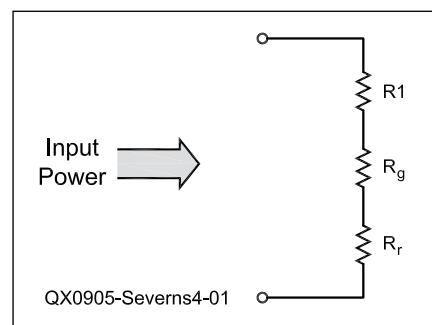


Figure 1 — An antenna input equivalent circuit. R_l represents the ohmic loss due to conductors, loading inductor series resistance, and so on. R_g represents the power dissipated in the soil by the near-field of the antenna. R_r is the radiation resistance, which accounts for the radiated power.

various numbers of ground surface radials, however, the height of the antenna may have to be modified to maintain resonance and the current maximum may actually be out on the radials or possibly even back up into the vertical. What this means in practice is that the fraction of the feed point impedance we attribute to R_r may not be converging to the ideal value from theory as we add radials or change radial lengths. For example,

¹Notes appear on page 42.

a resonant, very thin $\frac{1}{4} \lambda$ vertical over perfect ground will have $R_r = 36.2 \Omega$ but a real antenna may converge to a somewhat different value as we add radials and reduce ground loss.

With a $\frac{1}{4} \lambda$ vertical it is often assumed that if R_l is small, then R_g is simply $R_s - 36.2 \Omega$. This is not the case and should not be assumed. The radiation resistance varies as the ground system changes, and does not approach 36Ω until the ground system is relatively large. In a broadcast antenna with 120 radials 0.4λ long, this approximation is very good, but in the limited ground system typical of amateur antennas at HF, it is not. A detailed discussion of this point can be found in an article available on my Web site, "Radiation Resistance Variation with Radial System Design."⁴ (This may become a *QEX* article in the future.)

Because we are interested in the effect of efficiency on signal strength, it is handy to express efficiency (η) in terms of dB:

$$\eta = 10 \text{Log} \left(\frac{1}{1 + \frac{R_g}{R_r} + \frac{R_l}{R_r}} \right)$$

[Eq 1]

For 100% efficiency, $R_l = R_g = 0$ and $\eta = 0$ dB. If we increase R_l and/or R_g , η will decrease. For example 80% efficiency would be about -1 dB.

Experimental Tests

All of the measurements were made on 40 m, 7.2 MHz in most cases. I chose 40 m verticals for their manageable size. Even at that size, the ground system that had to be laid down and taken up numerous times, required over 2000 feet of wire.

I used five different antennas:

- A $\frac{1}{4} \lambda$, 1 inch aluminum tubing vertical, adjusted to resonate at 7.2 MHz.
- An $\frac{1}{8} \lambda$, 1 inch aluminum tubing vertical with three top loading wires sloping at roughly 45° , again, resonated at 7.2 MHz.
- An $\frac{1}{8} \lambda$, 1 inch aluminum tubing vertical with no top loading, but resonated to 7.2 MHz with a base inductor.
- A 40 m Hamstick mobile whip (about 7.5 feet high), the top section adjusted for resonance at 7.2 MHz.
- A Cushcraft R7000 vertical.

The minimum conceivable ground system for a vertical would be a single ground stake with a coaxial feed line back to the shack. In this case, the feed line acts as a

single random length radial. For these measurements I adopted this as the "zero radial" system, where the stake was a 4 foot copper-clad steel rod with $\frac{1}{2}$ inch Andrews Heliac, buried 6 inches below the ground surface, back to the shack. The ground system was improved progressively by adding 33 foot (no. 18 AWG) radials in the progression: 0, 4, 8, 16, 32 and 64. This was repeated for each antenna. A $\frac{1}{4} \lambda$ in free space is close to 33 feet at 7.2 MHz. As was shown in Part 2, however, the *electrical* length of the radials changes when the radials are placed close to the soil.⁵

The soil characteristics under the radial system were measured using the technique given in *QEX*.⁶ The average soil constants in the test field were: conductivity, $\sigma = 0.02$ S/m and relative dielectric constant, $\epsilon_r = 30$. I will refer to this as "N6LF soil."

For each number of radials and each antenna, two measurements were made: the input impedance and the relative signal strength at a point 1.8 wavelengths away from the test antenna, at an elevation angle of about 8 degrees. Because the number of radials affected the resonant frequency, each antenna was re-resonated by adjusting its height as the number of radials was changed.

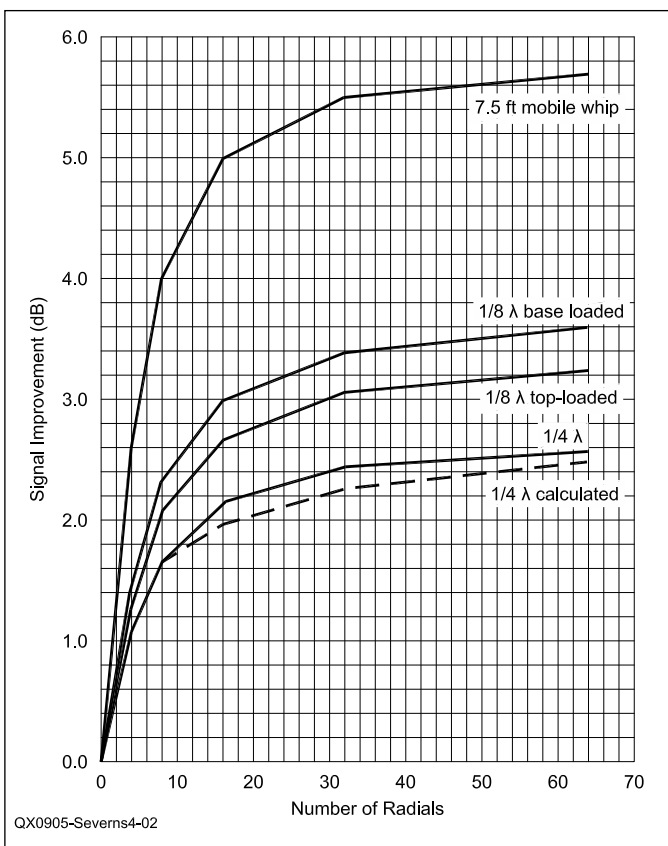


Figure 2—Typical improvement in signal as $\frac{1}{4} \lambda$ radials are added to the basic ground system (a single ground stake).

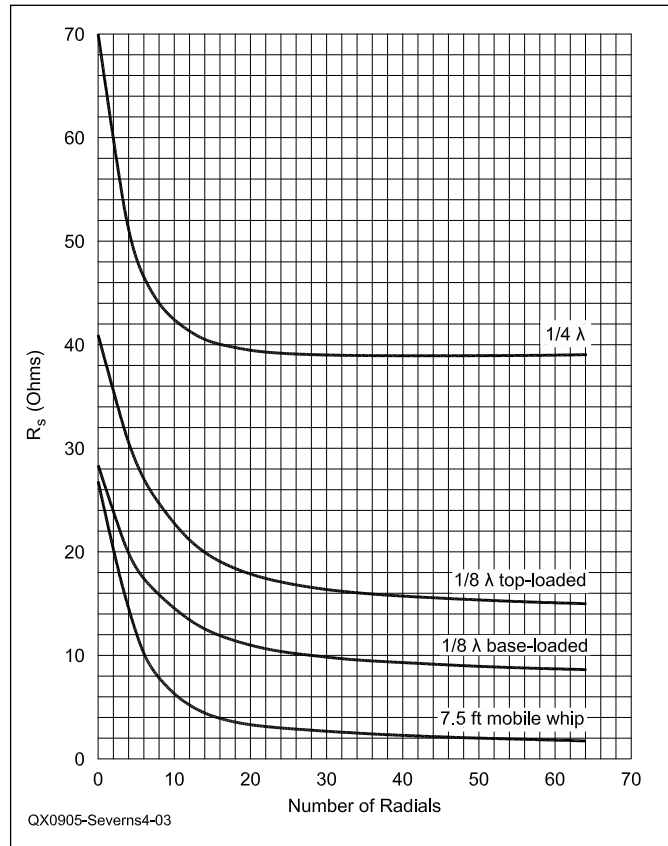


Figure 3—Measured input resistance (R_s) at resonance as a function of the number of radials.

Experimental Results

When we compare the results for different numbers of radials on a given antenna, the change in relative signal strength directly answers the question of how much signal improvement we get by adding radials. Typical test results are shown in Figure 2.

Note that the graph is in terms of the *improvement* in signal over the single ground stake with no radials for *each* antenna. The graph does *not* compare the relative worth between each antenna. Obviously a short, lossy mobile whip will yield much less signal (–10 dB or worse!) than the $\frac{1}{4} \lambda$ vertical.

The effect of radial number on input resistance (R_s) is shown in Figure 3.

In the case of the Hamstick mobile whip, I have subtracted R_I from the measured input resistance because it has a fixed value independent of radial number. R_I is determined by the loading coil Q . We can see that as we add larger numbers of radials the values for R_s begin to level out and approximate, but not equal, values for ideal lossless antennas.

Interpreting the Data

One of the interesting things about Figure 2 is that it shows that *the shorter and more heavily loaded the antenna, the more you have to “gain” from an aggressive ground system*. For example, the improvement for the $\frac{1}{4} \lambda$ vertical, going from 0 to 64 radials, is about 2.6 dB, but for the $\frac{1}{8} \lambda$ base loaded vertical it's more like 3.4 dB, and for the mobile whip, nearly 6 dB.

What's going on here? As I pointed out in my July 2000 *QST* article on ground systems, when we shorten an antenna but keep the input power the same, both the magnetic and electric field intensities in the immediate vicinity of the antenna increase dramatically.⁷ This translates to much higher ground losses. What we see in Figure 2 is that adding the radial system reduces these losses, but since the losses are higher to start with for the shorter antennas, the improvement is greater. No mystery!

From Figure 2 we can see that for all the test antennas, most of the improvement comes with the first 16 radials. As we add more radials beyond 16, there is still improvement but it is proportionately smaller. You gain perhaps another fraction of a dB going to 32 radials but by the time you reach 64 radials there isn't much change. The broadcast standard of 120 radials 0.4λ long is hard to justify for amateur use, particularly given the present price of copper wire!

Figure 2 also has a dashed line very close to the curve for the $\frac{1}{4} \lambda$ vertical. This is a prediction using Abbott's calculation method.⁸ I could have also added calculated lines for the other antennas and would have seen the same

reasonable correlation, but that would have really cluttered the graph so I left them off.

We do have to be a little careful in using these graphs as general guides. They represent experimental results over my particular soil, at one frequency. Can we really draw any general conclusions? In lieu of running tests on all possible soils, we can get a feeling for this by calculating the signal improvement for different soils using Abbott's calculation method. (See Note 8.) Typical calculated results for different soils, at 7.2 MHz, are shown in Figure 4. This graph starts at 8 radials and goes to 64 radials. Smaller numbers of radials are omitted because the underlying calculation becomes inaccurate as the angle between the radials increases beyond 45° , the 8 radial case. From a practical point of view this is not a serious limitation. As I pointed out in Part 2 in the Jan/Feb 2009 issue of *QEX* (see Note 5), and as the data in Figure 2 shows, a four-radial ground system has very minimal performance; 8, or better yet 16 radials, should be the minimum, except perhaps in an emergency.

For the soil over which these tests were done (N6LF), the calculated 8 to 64 radial change is about 0.8 dB. Going back to Figure 2 we see that the measured change for the $\frac{1}{4} \lambda$ vertical is 0.9 dB (8 to 64 radials). The calculation agrees quite well with the measurements. Figure 4 tells us that when the soil is better, a given number of radials gives somewhat less improvement and with poorer soils there is more improvement. Again, no surprise. If you have better soil, you have lower losses to start with, so the improvement will be less. But even with very good soil it's

still worthwhile to use at least 16 radials.

What about frequencies other than 40 m? There are a couple of complications to extending the 40 m work to another band. First, the graph in Figure 4 does not scale directly with frequency because the field intensity at a given distance (feet or meters), for a given base current, does *not* scale linearly with frequency. Second, at a given site the ground characteristics will vary with frequency. (See Note 6) The result is that the ground loss is not the same for the scaled antennas at other frequencies, even though the input power may be similar.

As we go down in frequency, soil conductivity typically decreases, which tends to increase ground loss but the relative dielectric constant goes up, which tends to decrease ground loss. For N6LF soil at 7.2 MHz, $\sigma = 0.020$ S/m and $\epsilon_r = 30$, but at 1.8 MHz, $\sigma = 0.013$ S/m and $\epsilon_r = 68$. The net effect on signal improvement (8 to 64 radials) is shown in Figure 5.

If you examine Figures 2 and 3 closely and compare the curves for the $\frac{1}{4} \lambda$ vertical, you may see something funny going on. In Figure 2, even when we go from 32 to 64 radials, there is still some improvement in signal. But if you look at Figure 3, there appears to be no change in R_s , so how can the antenna be more efficient? This same paradox shows up in the Brown, Lewis and Epstein data (see Note 1) taken 70 years ago, and has been the subject of comment ever since. What's going on? Several things are going on simultaneously. First, the number of radials is increasing, which reduces R_g . Second, we are steadily increasing the height

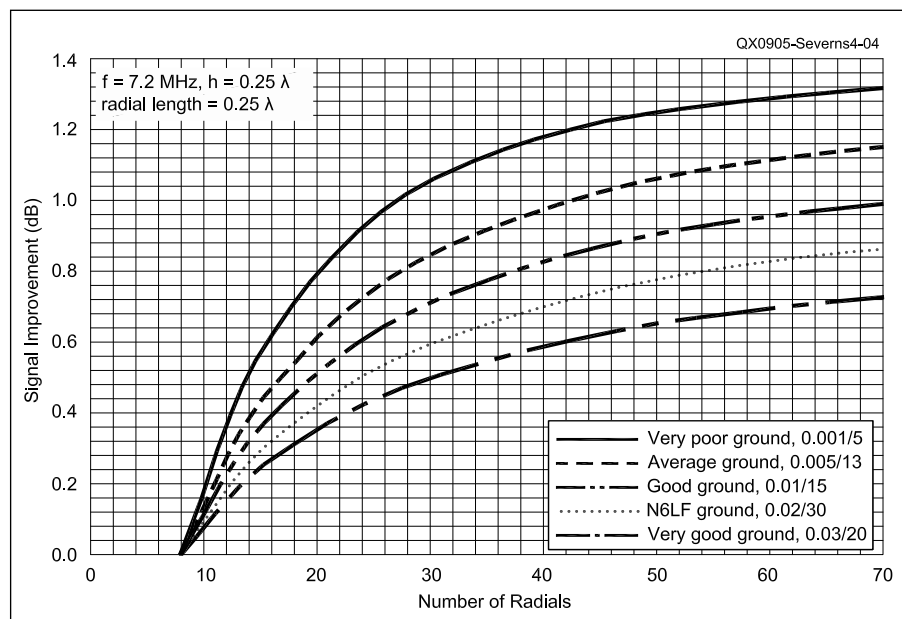


Figure 4 — Calculated signal improvement as we vary the number of radials over different soils with a $\frac{1}{4} \lambda$ vertical with $\frac{1}{4} \lambda$ radials at 7.2 MHz. Note: 0 dB is for the 8 radial case.

of the antenna to re-resonate it due to the effect of the radials on the ground, which we will look at shortly. This tends to raise R_s . In the case of the measurements for the $\frac{1}{4} \lambda$ antenna, the two effects cancel to some extent. Notice that for the other antennas, R_s is still trending down as signal strength goes up with number of radials. Altering the height as we add radials is not the full story, however, R_r is also affected by the radial system. (See Note 4.)

Additional Tests

In addition to the tests where antenna height and number of $\frac{1}{4} \lambda$ radials were the variables, I ran a few others. In one, I compared the performance of the $\frac{1}{8} \lambda$ top-loaded vertical with 64 radials, with and without, an $\frac{1}{8} \lambda$ circular ground screen (diameter = 36 feet) added over the radial fan. The addition of the ground screen made no detectable difference, which is in line with previous work. See Note 1. Obviously, if you have only a few radials, then a ground screen would help.

Modeling of gain versus radial number and radial length indicates that a larger number of shorter radials may be just as good or better than fewer longer radials, assuming both radial systems use the same amount of wire.⁹ To check this out I ran a test using the top-loaded $\frac{1}{8} \lambda$ vertical, comparing sixteen $\frac{1}{4} \lambda$ (33 ft) radials versus thirty two $\frac{1}{8} \lambda$ (17 ft) radials. In line with the modeling and also calculations, the signal strengths were almost the same. The feed point impedances were substantially different however. I had to lengthen the vertical to re-resonate it with the 32 short radials. This is a good example of the interaction between the feed point impedance and the radial system. If space is restricted, then more short radials in place of fewer long radials may work just fine, but to properly evaluate that option it would be best to do the modeling or calculation for a particular vertical and soil characteristics.

I made measurements on the R7000, with and without an external ground system, which showed that adding a 64 radial ground system had almost no effect on signal strength (+0.1 dB). This surprised me until I had an e-mail conversation with Joe Reisert, W1JR, the original designer. The antenna was designed to work without a ground system and although the antenna is physically less than $\frac{1}{4} \lambda$ on 40 m (25 ft), the loading is arranged so that it behaves more like a $\frac{3}{8} \lambda$. There are a set of 48 inch radials at the base, which are isolated from ground. The current maximum is well up into the antenna and the base is a high impedance point. The conventional wisdom, to which I have been a subscriber, is that even with a $\frac{1}{2} \lambda$ vertical, adding an extensive ground system

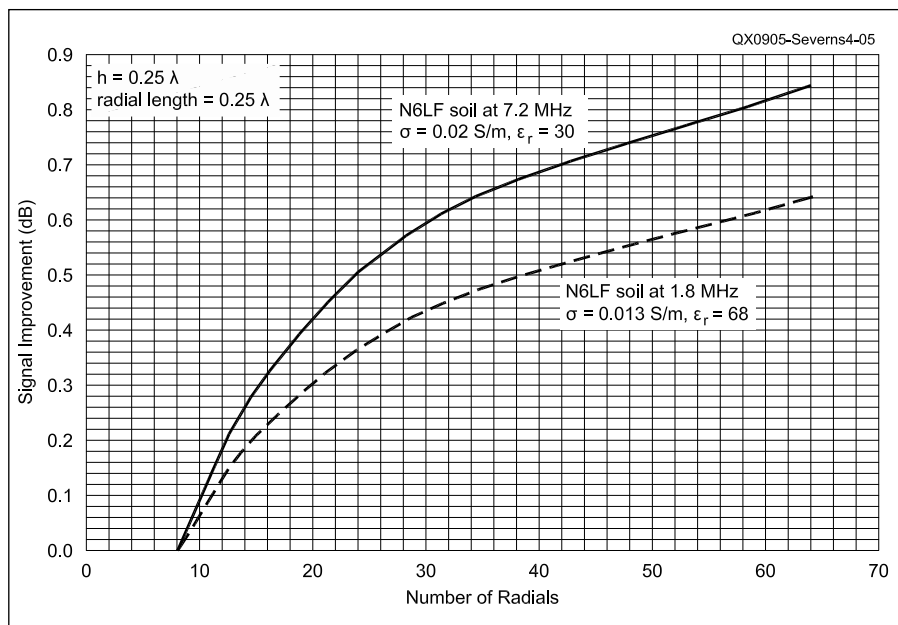


Figure 5 — Difference in signal improvement between 1.8 and 7.2 MHz over N6LF soil using the same vertical height and radial length in wavelengths (scaled with frequency). 0 dB is for the 8 radial case.

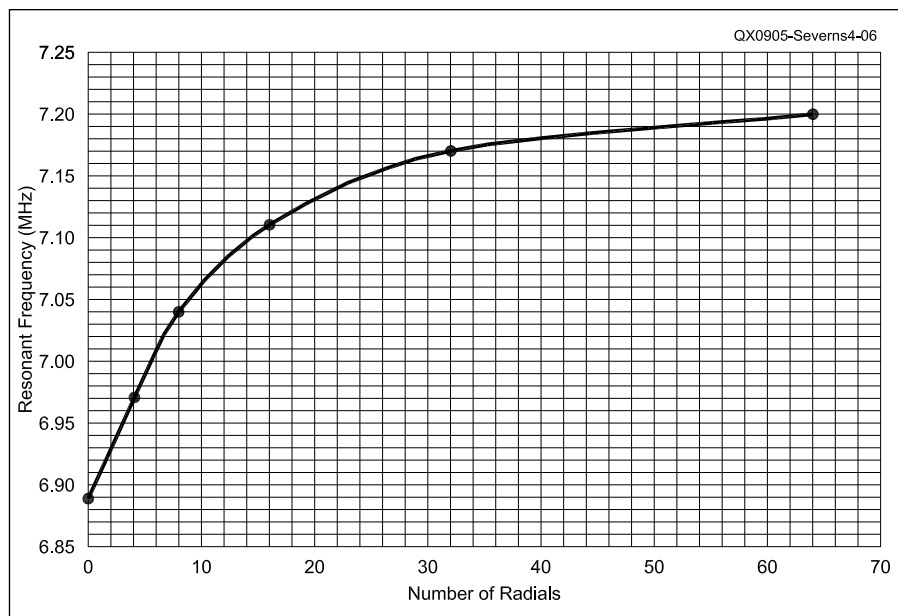


Figure 6 — Resonant frequency of a vertical antenna resonated at 7.2 MHz with sixty four 33 foot radials, as a function of the number of radials.

will improve performance. I did not see that here. This is a subject for more experiments, perhaps.

Measured Resonant Frequency

During the experiments, I found that changing the number of radials changed the resonant frequencies of all the antennas except the R7000. For example, using

the $\frac{1}{4} \lambda$ vertical, I laid down 64 radials and adjusted the height of the vertical so that it was resonant at 7.2 MHz. I then started removing radials (but not changing the height), measuring the resonant frequency as I went down to zero radials. The results are shown in Figure 6.

Obviously the resonant frequency is affected by the radials. You can of course re-

resonate the antenna by changing its height or loading. During the experiments for signal strength and input impedance, I adjusted the height to restore resonance at 7.2 MHz. With 64 radials resonance at 7.2 MHz was obtained with $h = 33$ feet 7 inches. With no radials, the 7.2 MHz resonant height was 32 feet 11 inches, 8 inches shorter.

What's going on? When there are no radials, only the ground stake and the random length of feed line, the resonant frequency is low primarily because the upper portion of the stake effectively adds to the antenna height. Even though the stake is driven into the soil, the top layer of soil, at least in summer when these measurements were made, is quite dry. The effective ground surface is actually somewhat below the physical surface. There was also some inductance in the lead connecting to the ground stake. As we add radials this effect is reduced but only slowly because, as shown in Part 2 (see Note 5), the radials are heavily loaded by their close proximity to the soil. They are resonant below 7.2 MHz so they are inductive at 7.2 MHz. This shunt inductance is across the

base of the antenna. As we add more radials we are adding more inductors in parallel, which reduces the effective reactance and increases the resonant frequency.

Conclusions

The answer to our original question, "Does laying the radials on the surface matter?" is a little clearer now. *For the same number of radials of the same length*, the efficiency will be pretty much the same whether buried or on the surface, but the effect on feed point impedance may be somewhat different. This can become a practical problem if the antenna tuning varies with the season (wet or dry or frozen ground). Radials lying on the ground surface really behave more like elevated radials even though they may be lying right in the dirt.

We can summarize all this with the following advice:

- Try to use at least sixteen $\frac{1}{4} \lambda$ radials.
- If you don't have the space for $\frac{1}{4} \lambda$ radials, lay down a larger number of shorter ones.
- More than 16 radials will help but give only a fraction of a dB over average or better soils.
- The shorter your antenna, the more you need a good ground system.
- The poorer your soil the more you need a good ground system.
- A surface-radial ground system will affect the resonant frequency and you may have to adjust the vertical height for that.
- Work hard at making the antenna itself more efficient. In other words, use high-Q loading coils, use top loading to minimize the size of loading coils, minimize conductor loss, and so on.
- Modeling and calculations seem to be in reasonable agreement with measurements and, with some caution, can usefully be used to estimate the magnitude of improvement when adding to a ground system.

Acknowledgments

This work was inspired by the classical articles by Jerry Sevick, W2FMI, which have served us so well.^{2, 10, 11, 12, 13} In many ways my experiments are just an update and reconfirmation of Sevick's work.

I want to thank Mark Perrin, N7MQ, for his help in making many of the measurements. Especially helping to drag the monstrously unwieldy chicken wire ground screen into position and out again.

In addition to the references already cited in this article, I have included several more related references, which the reader may find useful. See Notes 14 through 21.

Notes

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Experimental Determination of Ground System Performance for HF Verticals Part 5 160 Meter Vertical Ground System

How much will the signal strength and feed point impedance change as radials are added?

This experiment was actually the first of the series of experiments on ground systems that have been the subject of this series of articles. The experiment involved measuring the change in signal strength as radials are added to the ground system of a vertical antenna, beginning with four radials and going up to 64 radials. The intent was to determine the additional gain in signal for each doubling of radial number, and to determine the point of vanishing returns. In addition, the changes in feed point impedance due to changing radial number were of interest.

While the results of this initial experiment were quite interesting, a more important result was an appreciation of the difficulties of making these measurements accurately. This experience led to a modification in the test procedure and a shift to 40 m verticals, which have been described earlier.

Test Antenna Description

The test frequency for this experiment was 1.800 to 2.000 MHz. The vertical was 125 feet of no. 12 AWG insulated copper wire suspended from a Dacron line hung between two 150 foot poles.

At the base of the antenna there was an 18 inch diameter copper disk, as shown in Figure 1. The inner ends of the radials and

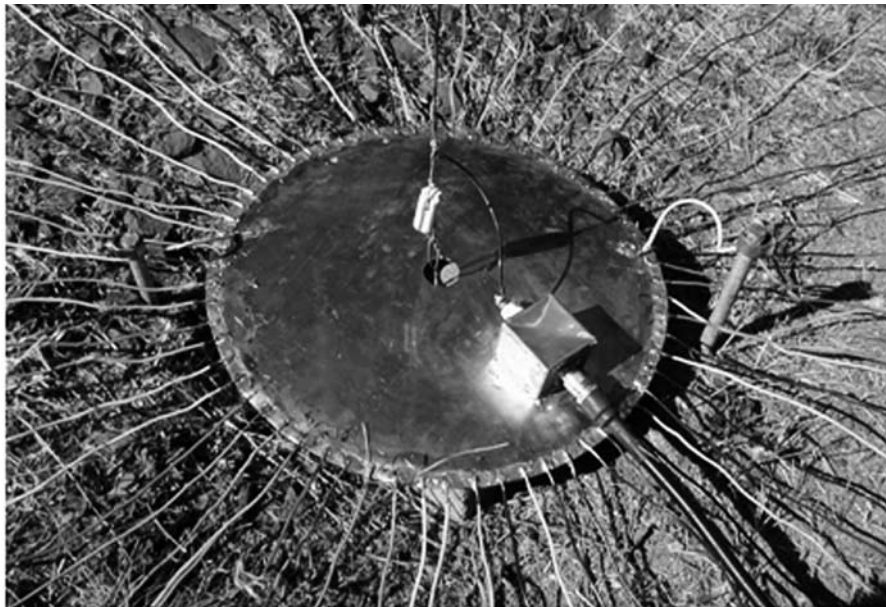


Figure 1 — This photo shows the antenna base with radials attached.

the shield of the coax feed line were attached to the disk. There were also two galvanized $\frac{5}{8}$ inch $\times$ 4 foot ground stakes connected to the disk. The radials were 130 foot lengths of no. 12 insulated (THHW) wire lying on the ground surface. Radials were put down in the sequence of 4, 8, 16, 32 and 64.

The terrain around the antenna was not flat, but rather on a narrow ridge about 40 to 50 feet wide. The result is that many of the radials were in part bent down at about a 45° angle as they ran down the steep slope on either side. Along the ridge, however, the radials are more or less level.

The test antenna was erected 700 feet to the east of my house with a 50 foot deep gully in between. The ridge is in a Douglas fir forest with 100 plus foot trees within 50 feet of the test antenna at some points. The radial system ran along the ridge and also down the sides of the ridge into the forest.

To excite the test antenna, between the house and the antenna there was a 700 foot length of 1½ inch coax, with an additional 75 feet of ½ inch coax. Both were Andrews heliax.

Measurement Equipment

The signal source was a Yaesu FT1000MP transceiver with two Bird Model 43 wattmeters on the output (forward and reflected power). The wattmeters were used to set the forward power to a constant 50 W and also to measure reflected power to calculate SWR. The SWR measurement is needed to correct for the power reflected from the antenna and not radiated. This correction was applied to the received signal amplitude.

The receiving antenna was a 10 foot vertical wire driven against a 4 foot ground stake, next to my house. The receiver was an HP3585A spectrum analyzer. The amplitude resolution was about ± 0.1 dB.

Base impedance measurements were made at the antenna using an N2PK vector network analyzer (VNA). The impedance measurements were accurate to better than 1%.

The test procedure was very straightforward. For each number of radials, the FT1000MP output was adjusted to 50 W and received signal strength on the spectrum analyzer recorded along with the SWR for that measurement and the input impedance at the base of the antenna.

Test Results

Three complete runs were made to verify repeatability of the measurements. Each run included a complete stepping through the number of radials in the sequence, 4, 8, 16, 32 and 64. Typical received (and corrected for SWR) signal strengths versus radial number are given in Table 1. This data is graphed in Figure 2.

The data in Figure 2 has one obvious oddity. You would expect that the incremental difference as the radial numbers are doubled would be monotonically decreasing as the radial number rises. The step between 16 and 32 radials does not do this and it appears that the value for 16 radials is too small. This anomaly was noted during the experiment, however, and checked carefully as the radial count was redone three times. The anomaly was there in all three cases. I have no explanation for this other than the irregularity of

Table 1

Typical Test Data for Received Signal Strength with $P_o = 50$ W.

<i>Number of Radials</i>	<i>Corrected Signal Strength</i>	<i>Relative Signal Strength</i>
4	−30.1 dBm	0.0 dBm
8	−29.3 dBm	0.8 dBm
16	−28.9 dBm	1.2 dBm
32	−28.0 dBm	2.1 dBm
64	−27.7 dBm	2.4 dBm

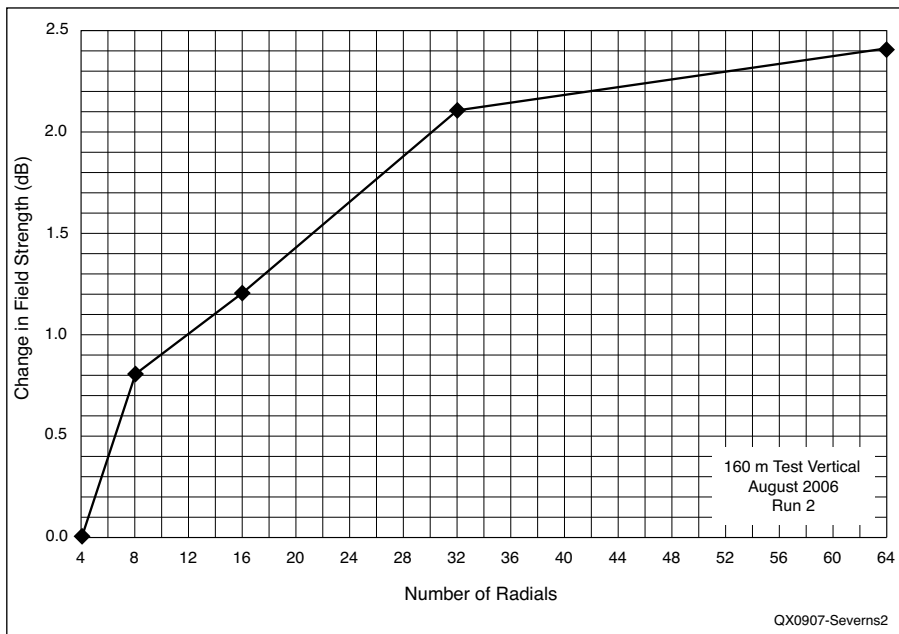


Figure 2 — Here is a graph of the typical signal strength change with radial number.

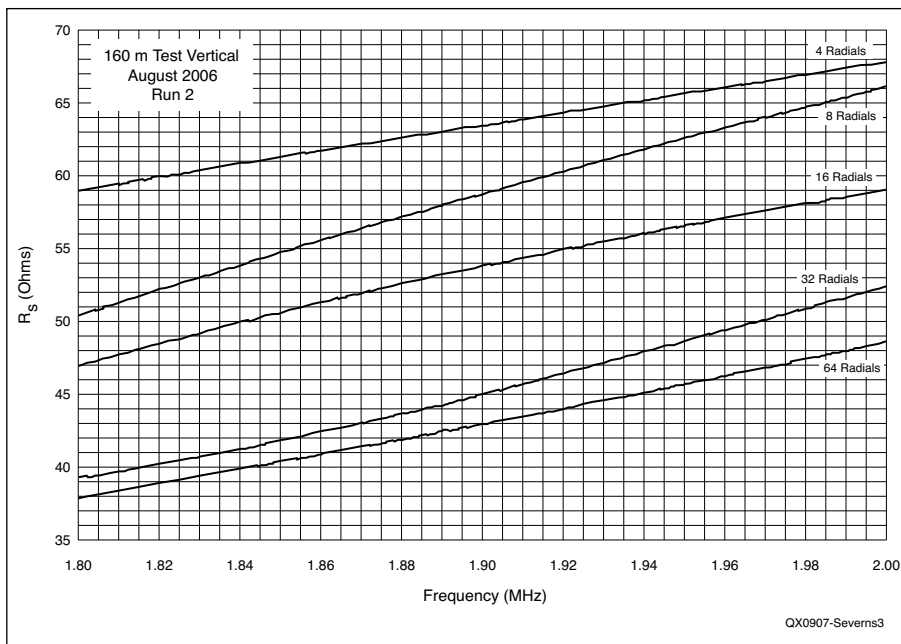


Figure 3— This graph gives the resistive part of the base impedance over the 160 m band for different radial numbers.

the site, which forced the radial layout to be far from flat or level. Later experiments with more regular radial systems on other antennas all showed the expected monotonic decrease in improvement with increasing radial number.

In any case, it's pretty clear that 32 radials do a good job and by 64 radials you are well into the region of vanishing returns. I certainly could not justify doubling the radial count to 128!

The results of feed-point impedance measurements are given in Figures 3, 4 and 5.

As discussed in Part 2 of this series, we would expect the resonant frequency to vary with the number of radials, due to the shift in radial resonance because of soil loading. The 40 m experimental work was done over an essentially flat pasture and the resonant frequency change was regular and monotonic. The gross irregularity of the ground surface in this earlier experiment, however, resulted in the erratic frequency changes shown in Figure 5. This problem was a primary reason for moving the experimental site from the narrow ridge to a pasture. Unfortunately, the 150 foot support poles were not available in the pasture so it was necessary to change the experimental frequency to 40 m to make the vertical height manageable.

Summary

This initial experiment helped me to understand the problems inherent in making accurate comparisons between different ground systems. I had to change the site, the test frequency, the test instrumentation and the test methodology to get to the point where I could have confidence in the test results and draw conclusions from them.

This experiment was by no means a failure, however. We can see that the change in signal strength is very much in line with what we saw in the 40 m work. It also supports the conclusion that we should use at least 16 radials, but when we use more than 32 radials we are definitely reaching the point of vanishing returns. For most amateur installations the Standard Broadcast ground system of one hundred twenty 0.4-wave-length radials could not be justified by any useful increase in signal strength.

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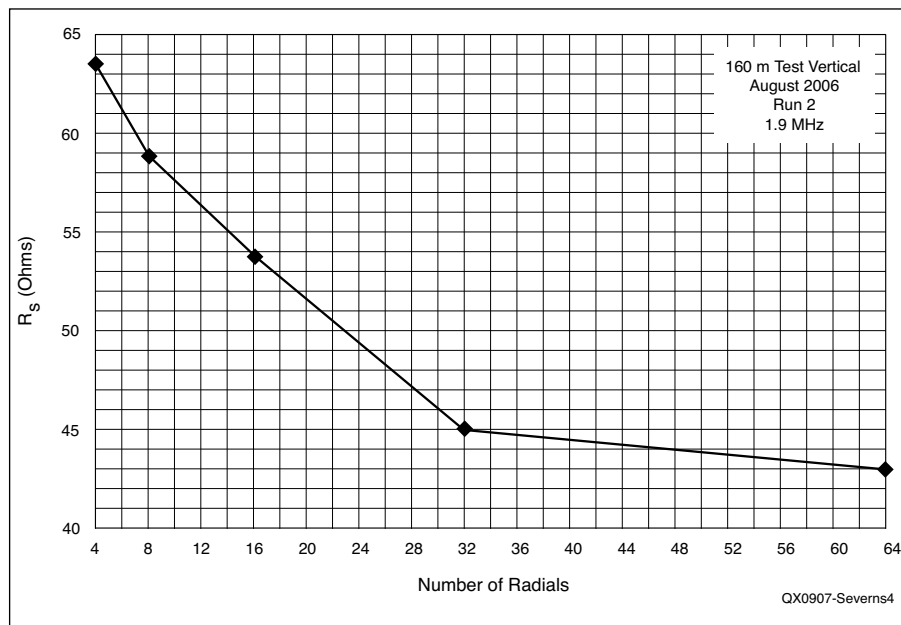


Figure 4 — This graph shows the base resistive component versus radial number at 1.9 MHz.

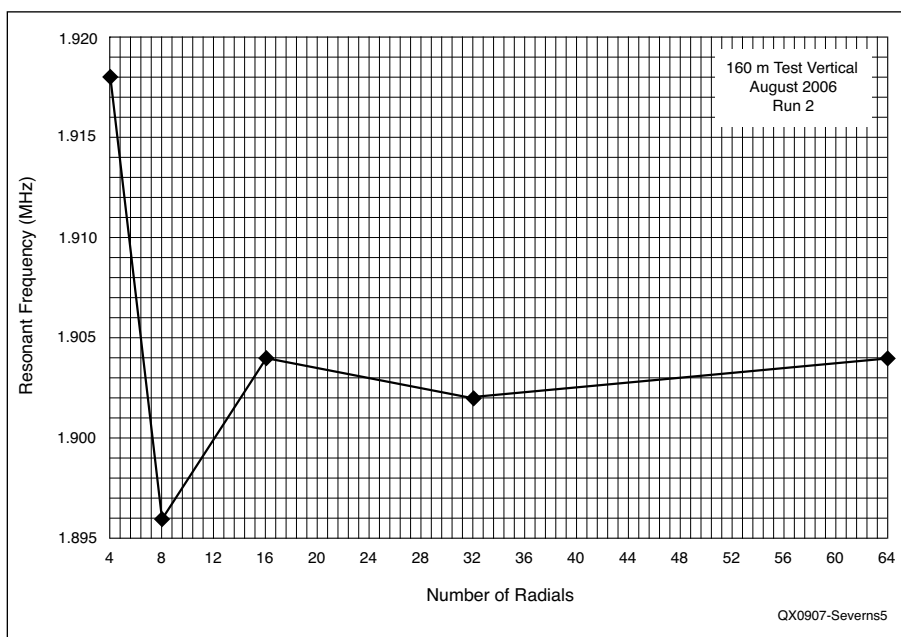


Figure 5 — This graph shows the antenna resonant frequency for different numbers of radials.

QEX

Experimental Determination of Ground System Performance for HF Verticals

Part 6

Ground Systems for Multiband Verticals

How much will the signal strength and feed point impedance change as radials are added?

The first five parts of this series have focused on ground systems for a single-band vertical (mostly on 40 m).^{1, 2, 3, 4, 5} This part of the series will address multiband radial systems, and give us an opportunity to see if the performance equivalence shown earlier between a large number of radials lying on the ground and a few elevated radials will hold with a multiband radial system.

The experiments were performed in two phases. The first was for radials lying on the ground and the second was for elevated radials. These represent two typical scenarios for amateurs: in other words, "Do I put the antenna in the back yard or up on the roof?" These are quite different arrangements, so the discussion is divided into two parts, beginning with the radials lying on the ground surface and then moving on to elevated radials.

The Test Antenna

For this series of tests I used a SteppIR III vertical antenna. The SteppIR has the advantage that its height can be adjusted to be resonant anywhere between 40 m and 6 m. The height adjustment is motorized and controlled remotely, so it is very convenient for tests on multiple bands.

¹Notes appear on page 24.

Test Frequencies

Most of the measurements were taken at spot frequencies of 7.2, 14.2, 21.2 or 28.5 MHz. I did make a limited number of measurements across each band, however, and some of those results will be discussed.

Radial System Configurations

For these experiments I made up four sets of thirty two $\frac{1}{4} \lambda$ radials, one set for each band (40, 20, 15 and 10 m). The radial lengths are given in Table 1 along with the corresponding free space $\frac{1}{4} \lambda$. As is the

usual practice, the radials are a few percent shorter than the free space $\frac{1}{4} \lambda$. The radials were fabricated from AWG no. 18 stranded, insulated wire.

Table 1
Description of Radial Lengths

Frequency (MHz)	Free-Space $\frac{1}{4} \lambda$ (Feet) / (Inches)	Radial Length (Feet)
7.2	34.2 / 410	33
14.2	17.3 / 208	16.8
21.2	11.6 / 139	11.3
28.5	8.63 / 104	8.4

Table 2
Total Length of Wire in Each Configuration.

Configuration	C1	C2 and C8	C3	C4	C5	C6	C7
Total Wire (ft)	2240	280	560	1056	528	264	132

Table 3
Transmission Gain (S21) in dB for Each Configuration Relative to C2 (0 dB).

Frequency (MHz)	C1	C2	C3	C4	C5	C6	C7
7.2	+0.9	0.0	+0.2	+0.9	+0.4	+0.1	-3.2
14.2	+0.8	0.0	+0.3	+1.0	+0.5	-0.6	-1.8
21.2	+0.3	0.0	+0.3	+0.8	+0.2	-1.1	-2.6
28.5	-0.6	0.0	0.0	+0.4	-0.5	-1.3	-3.8

During the experiments I used several different configurations:

C1) Sets of 32 single-band radials, one set at a time. In this way I had an optimized $\frac{1}{4} \lambda$ vertical over a ground system of thirty two $\frac{1}{4} \lambda$ radials on each band. These antennas were then measured individually on the appropriate single band.

C2) Four $\frac{1}{4} \lambda$ radials on each band (16 total radials), connected *all at the same time*.

C3) A repeat of C2 except using eight radials for each band (32 total radials).

C4) Thirty two 33 foot radials.

C5) Sixteen 33 foot radials.

C6) Eight 33 foot radials.

C7) Four 33 foot radials.

C8) For some elevated radial tests, I used four $\frac{1}{4} \lambda$ radials on each band, *one set of radials at a time*. The set of four was chosen for the particular band.

C1 and C8 were used for comparison purposes in that they represent a monoband antenna on each band. Obviously with a multiband antenna you would not run out to the antenna and change the radials whenever you changed bands! But this can give us feeling for any compromise in going from monoband to multiband verticals.

C2 represents the most common multiband ground system in general use both for elevated and ground surface radial systems, and so it was an obvious choice. I could have chosen many other possible combinations but those I did choose are at least reasonable. In particular I wanted to show that a few long radials (C6 and C7) don't work very well whether on the ground or elevated. Table 2 shows the total length of wire in each configuration.

Radials Lying on the Ground

The experimental results for radials lying on the ground are shown in Tables 3, 4 and 5. In Table 3 the values for S21 are in dB *relative* to the measured S21 value for C2 (0 dB). This was done to make it easier to compare each configuration to the de facto standard (C2).

The results for C7 show the same problem when used with a multiband vertical as shown earlier for a single band vertical — the ground loss is very high. Increasing the radial number from 4 to 32 (from C7 to C4) shows improvement.

C2 is our “standard” ground system (at least in practice) and we can see that its performance in comparison to the other configurations is quite good. It is true that individual sets of 32 radials on each band (C1) are somewhat better (except on 10 m,

for which I have no explanation!) but the compromise is less than 1 dB. Even though C2 has only four radials cut for 40 m, the other twelve shorter radials seem to take up most of the slack, and we do not see the very poor performance that four radials by themselves displayed. By doubling the number of radials in C2 to eight for each band (C3), we see some improvement over C2, although it's only a fraction of a dB.

The best performer is C4, which is 0.4 to 1 dB better than C2, depending upon the band. C4, however, requires almost four times as much wire. If we cut the amount of wire in half (C5) we still have some improvement over C2 (with the exception of 10 m). C3 and C5, which use approximately the same amount of wire, behave very similarly.

In the final analysis it appears that the standard ground system (C2) works just



Figure 1 — Here is a view of the vertical with elevated radials.

Table 4

Physical Height of the Vertical for Each Frequency and Ground System Configuration.

Configuration Frequency (MHz) (Inches)	Free Space $\frac{1}{4} \lambda$ (Inches)	C1 (Inches)	C2 (Inches)	C3 (Inches)	C4 (Inches)	C5 (Inches)	C6 (Inches)	C7
7.2	410	391	406	394	391	386	371	369
14.2	208	201	202	201	198	199	200	201
21.2	139	137	137	137	137	137	137	138
28.5	104	103	102	102	102	102	103	104

Table 5

Measured Feed Point Impedances With the Vertical Height Adjusted for Resonance at the Test Frequency.

Configuration Frequency (MHz)	C1 (Ohms)	C2 (Ohms)	C3 (Ohms)	C4 (Ohms)	C5 (Ohms)	C6 (Ohms)	C7 (Ohms)
7.2	40.0	54.4	51.7	40.0	43.5	56.3	92.4
14.2	35.1	50.0	44.5	42.7	51.2	62.4	85.8
21.2	36.0	40.5	38.4	42.0	48.9	66.3	102.9
28.5	34.4	48.2	39.3	43.8	51.6	67.8	105.6

fine. You can add more wire and get some improvement but whether that improvement is worthwhile depends on the user.

As shown in Tables 4 and 5, there is some interaction between the tuning or resonant height of the vertical and the individual ground system configurations. We've seen this effect in earlier experiments. The heights shown are a bit of an approximation. The control unit display for the SteppIR gives the length of the tape (the vertical conductor) above a certain point but between that point and the actual ground radial plate there is approximately another 12 inches of wire. The wire is bent within the base housing so you can't assign an accurate additional length. I have used 12 inches as a reasonable approximation.

The measured feed point impedances are given in Table 5.

Elevated Radials

Having four sets of 32 radials (one set on each band) on hand from the ground surface tests I decided to use these same radials for the elevated radial tests. With the exception of C1 and C3, I used the same configurations (C2, C4-C7) for the elevated tests. In the elevated radial testing, I used C8 in place of C1. Like C1, C8 is not practical, being a series of monoband verticals, but it serves as a reference against which to judge the compromise from using a multiband radial system. For comparisons between elevated and ground surface radials I have added a column (C1) to Tables 7 and 9 for the *on-the-ground* data associated with C1. We will use these when we discuss elevated versus ground radials.

A photograph of the experimental arrangement for the elevated radial tests is shown in Figure 1.

Because of the need for easy access to the radial base plate to make the many changes in radial configuration, I had to place the base of the antenna only 6 feet above ground.

Six feet high for the base is a bit low if we want to improve the feed point match by sloping the radials downward. In free space the input impedance of a 4-radial ground-plane antenna is about 22 Ω . As we bring the antenna closer to the ground, the impedance will vary around this number but in general is well below 50 Ω . Often the SWR will be high. One common means to improve the match is to slope the radials downward from the base, which raises the feed point impedance and lowers the SWR. Because of the limited height at the center, I could only lower the outer ends of the radials a small amount. Keep this in mind when we look at the measured impedances and SWR plots.

Experimental results are given in Tables 6, 7 and 8. A few of the columns have blanks. These are cases where that configuration, on that band, performed so poorly as to be unac-

Table 6

Transmission Gain (S21) in dB for Each Configuration Relative to C2 (0 dB).

Frequency (MHz)	C2 (dB)	C4 (dB)	C5 (dB)	C6 (dB)	C7 (dB)	C8 (dB)
7.2	0.0	-0.1	-0.2	-0.2	0.0	0.0
14.2	0.0	+0.2	-0.8	-4.0	—	+0.2
21.2	0.0	+0.4	+0.2	+0.2	—	+0.4
28.5	0.0	+1.1	+1.8	+0.7	—	+0.2

Table 7

Physical Height of the Vertical for Each Frequency and Configuration.

Configuration Frequency (MHz)	Free Space $\frac{1}{4} \lambda$ (Inches)	C1 (Inches)	C2 (Inches)	C4 (Inches)	C5 (Inches)	C6 (Inches)	C7 (Inches)	C8 (Inches)
7.2	410	391	403	397	397	400	403	403
14.2	208	201	208	190	180	150	—	208
21.2	139	137	143	142	143	145	—	142
28.5	104	103	104	100	97	88	—	104

Table 8

Measured Feed Point Impedances with the Vertical Height Adjusted for Resonance.

Configuration Frequency (MHz)	C2 (Ohms)	C4 (Ohms)	C5 (Ohms)	C6 (Ohms)	C7 (Ohms)	C8 (Ohms)
7.2	43.4	42	41.0	42.1	43.0	43.0
14.2	34.2	38.9	41.1	83.9	—	33.9
21.2	36.8	52.3	49.5	48.4	—	31.4
28.5	23.9	34.8	38.3	73.2	—	24.5

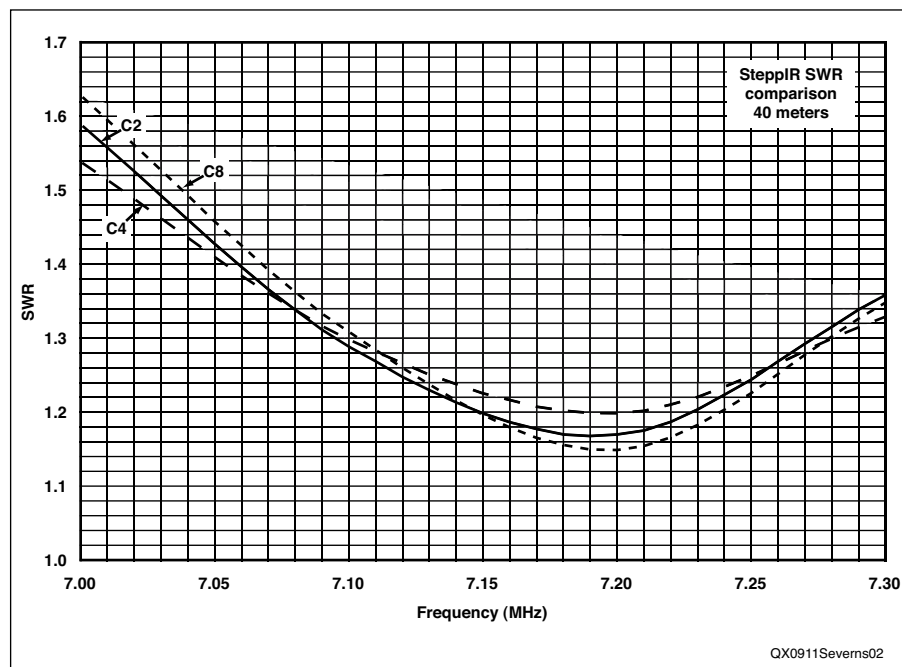


Figure 2 — Feed point SWR comparison on 40 m.

ceptable and I didn't see any point in recording that information.

From the data in Table 6, the standard multiband radial system (C2) appears to work very nearly as well as C4 and it takes only a quarter as much wire! The only band on which C4 appears to have a significant advantage is 10 m. C2 is also very close to C8 so there is very little compromise from the monoband case. As we move to fewer long radials (C5-C7) we see there is an immediate problem on 20 m, where the gain starts to fall quickly. From Table 7 we see that on 20 m the resonant height of the vertical starts to change radically as we go to fewer long radials, so clearly there is some funny business going on. This is related to the fact that

$\frac{1}{4} \lambda$ radials on 40 m are close to $\frac{1}{2} \lambda$ long on 20 m. Except on 20 m, C5 and C6 seem to be okay on 15 and 10 m, but by the time we get to C7 (four 33 foot radials) the performance was so poor I haven't even entered the data. The four long radials don't even work well on 15 m, where they are close to $\frac{3}{4} \lambda$ long.

From a loss point of view there appears to be little advantage to using anything other than the standard four radials cut for each band (C2). There is, however, the question if there is any matching (SWR) improvement from using more wire — for example C4 instead of C2. Figures 2 through 5 show a comparison of the feed point SWR between C2, C4 and C8 on the four bands.

On 40 m the differences are insignificant.

On the higher bands we see little difference between C2 and C8. C2 is behaving pretty much as we would expect. However, C4 does seem to offer some improvement above 40 m. It is especially noticeable on 15 m, where the 32 radials are all near $\frac{3}{4} \lambda$ resonance. From some of my earlier work I was not surprised that increasing the number of radials beyond four did not give much improvement in S21, but I was expecting to see much flatter SWR curves. This just doesn't seem to happen on 40 m but does appear on 15 m with $\frac{3}{4} \lambda$ radials.

We should keep in mind that the feed point impedances and associated SWR will be affected by the height above ground, which in this case is very low. For well

Modifying the Ground Radial Connections on the SteppIR

Before conducting the experiments, I modified the ground radial connection on the standard SteppIR and also made up a special feed line choke that would have an impedance greater than 1000 Ω on all bands.

As the SteppIR comes from the manufacturer, it has a single no. 12 brass machine screw to which the ground radials can be attached. I felt this was not adequate and certainly not very convenient for the many radial changes necessary during the experiments. I changed the single brass no. 12 screw to a pair of $\frac{1}{4}$ -20 machine screws spaced about 6 inches apart, as shown in Figure 1A.

I then fabricated an aluminum disk with fifteen $\frac{1}{4}$ -20 bolts with wing-nuts around its perimeter. The disk was attached to the base of the SteppIR housing as shown in Figure 2A.

For all the measurements in the experiments, but particularly for the elevated radial measurements, I wanted to have a common mode choke (balun) in the feed line and the cabling at the base of the antenna. The choke I used



Figure 1A — Modified radial attachment scheme for the SteppIR.

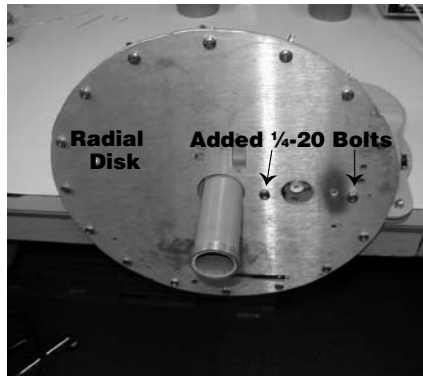


Figure 2A — SteppIR with radial disk attached.



Figure 3A — Common mode choke for the feed line.



Figure 4A — Chokes installed in the feed line and control cables at the base of the antenna.

is shown in Figure 3A. The choke has 6 turns of RG8X coaxial cable wound on two stacked type 43 cores (Fair-Rite #2643803802, available from Mouser Electronics). Also shown in the picture is the probe from the HP4815A vector

impedance meter used for impedance measurements. The measured shunt impedance was between 2 and 3 k Ω from 7 through 30 MHz.

Figure 4A shows both the chokes installed at the base of the antenna.

elevated radials, where the slope can be adjusted to provide a better match, the results may be much better than shown here.

Elevated Versus Ground Radials

Another key question is “How do the elevated radial systems compare to a large number of radials on the ground on each band?” Table 9 makes that comparison using the results from this series of experiments. C1 is used as the reference (0.0 dB).

C1 uses radials lying on the ground surface and C2, C4 and C8 are elevated. When we compare the signals for C1 to those for C8, which is a direct comparison between four elevated radials against 32 ground surface radials, one band at a time, we see only small differences: four elevated radials seem to perform much the same as large numbers of ground surface radials. This is in keeping with what we saw in Part 3, only now extended to bands from 40 through 10 meters.

C4 (which is thirty two elevated 33 foot radials) is also only marginally different from C1 and C2 except on 10 m, where the difference is 1.4 dB. Considering it has four times the wire, I doubt it’s justified.

Some Final Comments

In summary, I don’t see any compelling reason to use more than four radials on each band for a multiband vertical. The “standard” system (C2) does in fact seem to work well. If you want to lay out or hang up more wire, you can get some small improvement but generally the maximum improvement seems to be on the order of 1 dB or less, although the improvement might be somewhat higher over poorer soil than mine. In a way, this was a bit of a disappointment. It would have been nice to discover some magic new ground system for multiband verticals, but that was not to be. All I’ve really accomplished is to show that the old standard works just fine, and it appears that a few elevated radials can work as well as a large number of on-the-ground radials! Be careful, however! As I pointed out earlier in the series, elevated monoband radial systems with only a few radials are very susceptible to local effects that can cause unequal radial currents, which can degrade performance.

Keep in mind when comparing the data in this part with some of the data reported in earlier parts of this series, that this set of measurements were made in mid-summer when the temperature had been 85° and 108° F over the preceding month. The soil will have dried out considerably compared to that for most of the earlier experiments. This can cause the impedance and S21 measurements to vary substantially between seemingly identical experiments. This is why I emphasized in Part 1 the need to do all com-

Table 9

Transmission Gain (S21) in dB for Each Configuration Relative to C1 (0 dB).

Frequency (MHz)	C1 (dB)	C2 (dB)	C4 (dB)	C8 (dB)
7.2	0.0	+0.2	+0.1	+0.1
14.2	0.0	+0.1	+0.3	+0.3
21.2	0.0	-0.5	+0.4	-0.1
28.5	0.0	-0.3	+1.1	-0.1

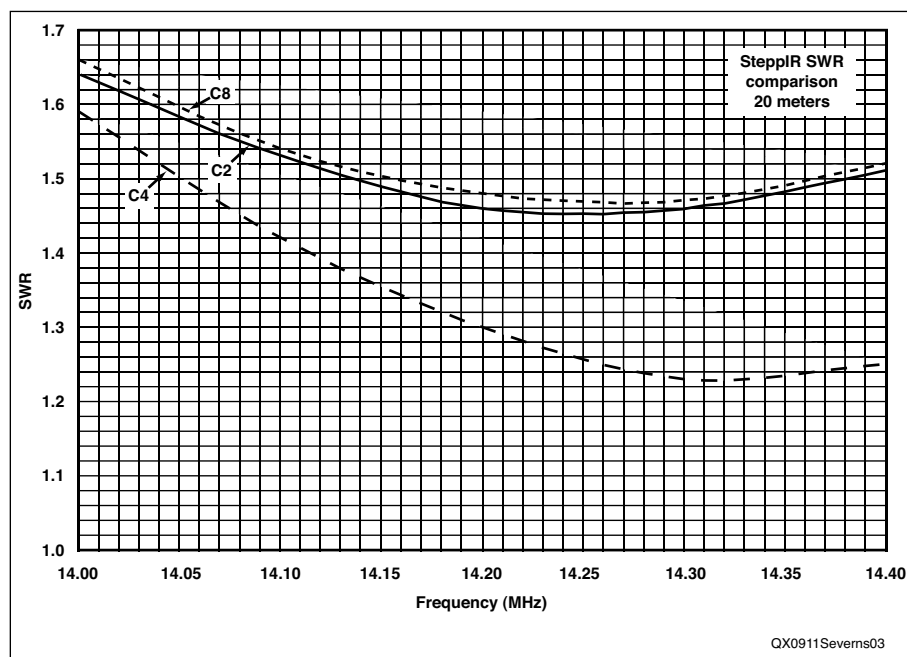


Figure 3 — Feed point SWR comparison on 20 m.

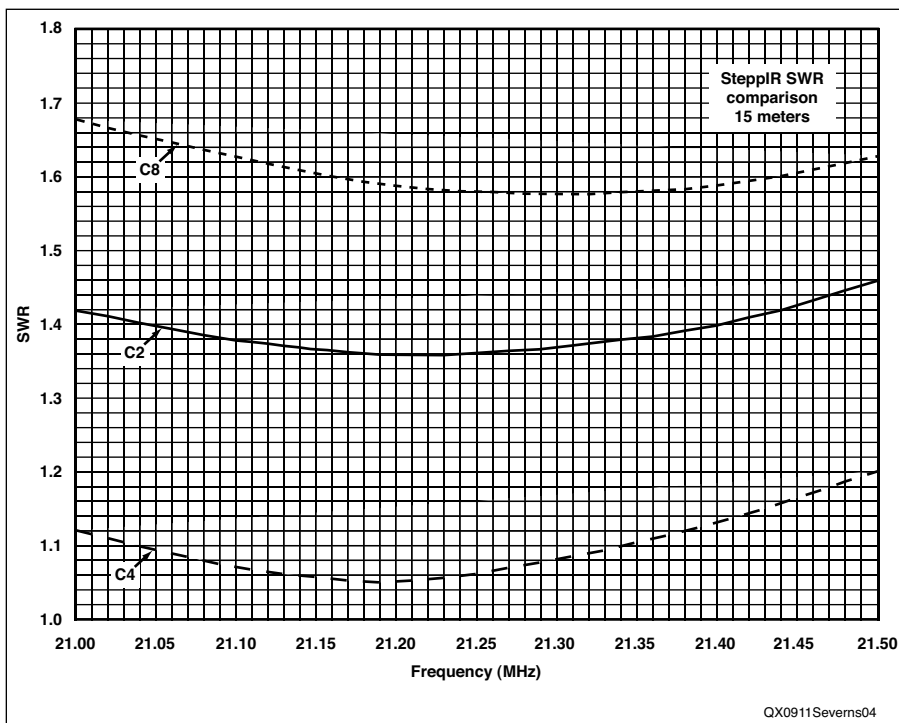


Figure 4 — Feed point SWR comparison on 15 m.

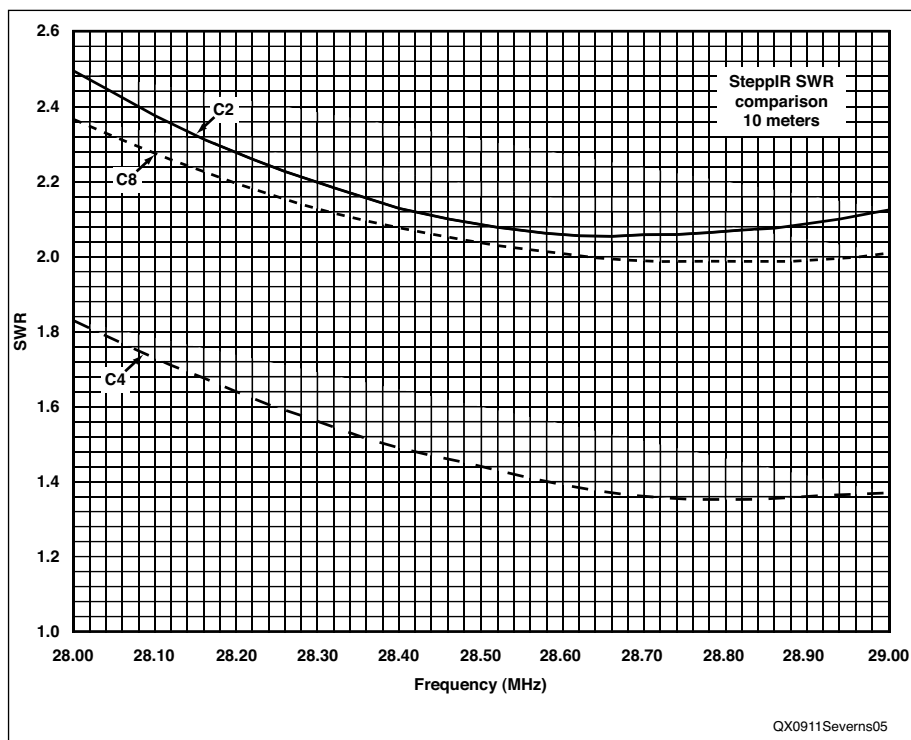


Figure 5 — Feed point SWR comparison on 10 m.

parison experiments in as short a time interval as possible. This sensitivity to changes in ground characteristics is also the reason I have emphasized that the specific numbers derived from these experiments must *not* be taken as absolutes. They are intended only to show the trends in performance between different ground systems. In addition, the frequency range in this series of tests goes much higher than those for the earlier experiments. The soil characteristics at a given location and time will vary with frequency.⁶ In other words, your mileage may vary!

Despite the extensive experimental work reported in this series there will still be many unanswered questions regarding ground systems for verticals. Answers will have to be deferred to future experiments and computer modeling. Hopefully, others will be inclined to join in this effort making their own contributions. Of course not all questions have to be answered experimentally. As some of this work has indicated, *NEC* modeling can shed a lot of light on many questions, although in the end it's always more convincing if there is at least some experimental confirmation.

Acknowledgement

I would like to express my appreciation to Mike Mertel, K7IR, for the loan of the SteppIR vertical antenna used in these experiments. That antenna made the experiments much easier. I would also like to thank Mark Perrin, N7MQ, for his help at some key points in the experiments, when another hand was really helpful.

Rudy Severns, N6LF, was first licensed as WN7WAG in 1954 and has held an Extra class license since 1959. He is a consultant in the design of power electronics, magnetic components and power-conversion equipment. Rudy holds a BSE degree from the University of California at Los Angeles. He is the author of two books and over 80 technical papers. Rudy is an ARRL Member, and also an IEEE Fellow.

Notes

¹Rudy Severns, N6LF, "Experimental Determination of Ground System Performance - Part 1," *QEX*, Jan/Feb 2009, pp 21-25.

²Rudy Severns, N6LF, "Experimental Determination of Ground System Performance - Part 2," *QEX*, Jan/Feb 2009, pp 48-52.

³Rudy Severns, N6LF, "Experimental Determination of Ground System Performance - Part 3," *QEX*, Mar/Apr 2009, pp 29-32.

⁴Rudy Severns, N6LF, "Experimental Determination of Ground System Performance - Part 4," *QEX*, May/June 2009, pp 38-42.

⁵Rudy Severns, N6LF, "Experimental Determination of Ground System Performance - Part 5," *QEX*, Jul/Aug 2009, pp 15-17.

⁶Rudy Severns, N6LF, "Measurement of Soil electrical Parameters at HF," *QEX*, Nov/Dec 2006, pp 3-9.

Experimental Determination of Ground System Performance for HF Verticals

Part 7

Ground Systems With Missing Sectors

Here is the author's research on radial systems that do not make a full circle around the vertical antenna.

A very common problem with vertical ground systems is the impracticality — in many situations — of laying down a symmetric circle of radials. Some object, frequently a structure or a property line, may make it impossible to place radials in certain areas around or near the base of the antenna. I have received many questions on this subject so I decided to do some experiments where I compared the signal strength (S_{21}) of a $\frac{1}{4}\lambda$ vertical antenna that has a full 360° radial fan to one with a substantial portion of the radial fan missing in one sector.

The first part of the experiment was done at four frequencies: 7.2, 14.2, 21.2 and 28.5 MHz. The second part the experiment was done at 7.2 MHz only.

Radial Fan Configurations

For this series of tests I chose to use a symmetric 360° radial fan with thirty two 33 foot radials ($\frac{1}{4}\lambda$ on 40 m) as the reference configuration (C1). As shown earlier in this series, a radial system with thirty two $\frac{1}{4}\lambda$ radials is usually pretty good. You can add more radials, but the gain is relatively small, so a 32-radial system is a good compromise, and probably more typical of amateur installations. The radials were close to $\frac{1}{4}\lambda$ on 40 m. Figure 1 shows a plan view of the initial radial fan geometries.

The four 180° sectors were arranged in relation to the receiving antenna as follows:

- 1) Radials toward (C2),
- 2) Radials away (C3),
- 3) Radials to the left (C4), and
- 4) Radials to the right (C5).

Both right and left configurations, which ideally should be identical, were run as a check on the consistency of the measurements.

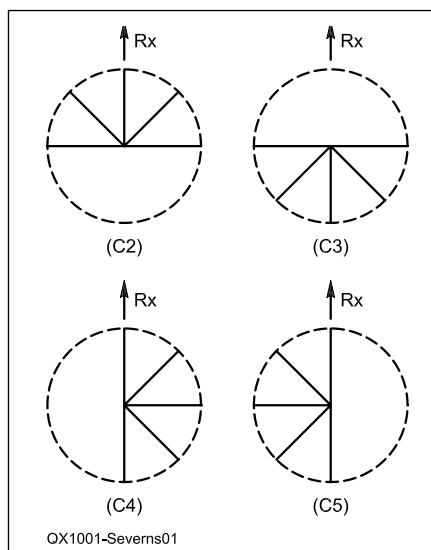


Figure 1 — Missing sector radial layouts.

After running tests using configurations C1 through C5, I realized that some additional radial configurations might be interesting. In particular I wanted to see how much adding some short radials in the missing sector would improve things.

I added the configurations shown in Figure 2 to the experiment:

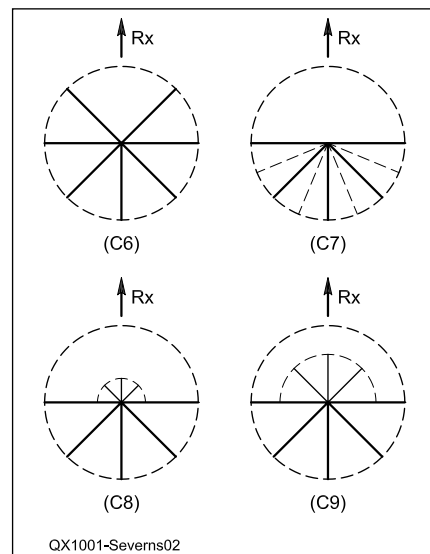


Figure 2 — Additional asymmetric ground systems.

Table 1

Effect of a 180° Sector Ground System on Signal Strength (S_{21}) in a Given Direction Relative to the Receive Antenna

Frequency (MHz)	C2 Toward RX (dB)	C3 Away from RX (dB)	C4 Left (dB)	C5 Right (dB)
7.2	-0.42	-1.91	-0.82	-0.94
14.2	-0.57	-2.42	-1.20	-1.24
21.2	-0.69	-3.00	-1.24	-1.33
28.5	-0.55	-3.23	-1.26	-1.58

Table 2
 S_{21} Test Results for the Added Radial Configurations

Radial Configurations	$ S_{21} $ Referenced to C1 (0.0 dB)
C6	-0.44
C3	-1.91
C7	-1.39
C8	-1.52
C9	-0.34

5) A 90° missing sector (7 radials removed, 25 radials remaining) (C6). The axis of the missing sector was pointed at the receiving antenna.

6) To C3, which has 17 radials facing away, I added an additional sixteen 33 foot radials between the seventeen already there (33 radials total) (C7). The missing 180° sector was facing the receiver.

7) To C3 I added fifteen 8.5 foot radials in a fan towards the receiving antenna. These are $\frac{1}{16} \lambda$ radials on 40 m (C8). C9) To C3 I added fifteen 17 foot radials in a fan towards the receiving antenna. These are $\frac{1}{8} \lambda$ radials on 40 m.

Test Results

Modeling ground systems with missing sectors using *NEC* indicates that compared to a full 360° system we should see both a reduction in the peak signal and a distortion in the pattern; in other words, a front-to-back ratio not equal to 0 dB.

Experimental results are given in Tables 1 and 2. Note that Tables 1 and 2 show the *difference* in dB from the 360° radial fan (C1), which is the reference.

Clearly sector radial systems have an impact on the radiated signal. In the direction of the remaining radials the signal loss is on the order of 0.5 dB, but in the direction of the missing sector the loss is from 1.9 to over 3 dB. If you have a 3 dB loss, that means you have lost half your power. Not good!

The test results qualitatively agree with *NEC*, the peak amplitude is reduced and the pattern is distorted when only a partial radial

fan is employed. The radial system used for the tests reported in Table 1 has 33 foot radials, which of course are long for frequencies above 7.2 MHz. As we saw in the discussion for multi-ground systems (Part 6), the system with all 40 m radials gives the best performance, even better than if we used thirty two $\frac{1}{4} \lambda$ radials tailored for each band.

The test results for radial configurations C6 through C9 are given in Table 2. All of these tests were done at 7.2 MHz.

The first thing we see is that omitting the seven radials in a 90° sector (C6) does not seem to do too much harm, only -0.44 dB. Eliminating all the radials in a 180° sector (C3) is not good, however (-1.91 dB). The loss jumps by almost 1.5 dB over the 90° case!

Taking the radials removed from C1 (to form C3) and adding them between the remaining radials in C3 (C7) helps a little bit, reducing the loss by 0.5 dB. If, instead, we add fifteen $\frac{1}{16} \lambda$ radials (C8) in the missing sector we get a similar improvement, about 0.4 dB. Despite some improvement, the signal loss for both C7 and C8 is still substantial. What really seems to help is to put fifteen $\frac{1}{8} \lambda$ radials (C9) in the missing sector. Unfortunately, that may not always be possible.

Some Closing Comments

Overall, it's pretty clear both from modeling and experiment that sector ground systems can reduce your signal substantially in some directions and produce a distorted pattern.

What can we do about this? The first thing is to remember that the field intensity around the vertical increases rapidly as we get near the base of the antenna.¹ If we move the base of the antenna away from the obstacle as little as $\frac{1}{16} \lambda$ or better yet $\frac{1}{8} \lambda$, so that we can have at least some radials in the sector towards the obstacle, the losses will be reduced. As shown above, $\frac{1}{8} \lambda$ spacing can

be quite effective. In the process of moving the base away from the obstacle you may have to shorten some of the other radials on the side away from the structure but that may be acceptable. Another possibility would be to move the base from the side of the building to a corner which might allow the radial fan to be increased from 180 to 270°. As the test data shows, this can be very helpful.

These experiments were done in an ideal situation. There was no actual structure next to the antenna. In addition to the losses we see in this idealized situation, it is very likely that the structure blocking the radial fan will increase the loss. It is difficult to estimate how much the loss will increase, but it's not likely that the building will improve your signal! Another factor to consider is the soil characteristics. My soil, over which these tests were conducted, would be rated as good or even very good, depending on the time of year. Poorer soils would result in even larger negative effects due to the use of a sector ground system than those shown in Tables 1 and 2.

What I have shown here represents only a few of many possibilities. It's not possible to experimentally examine all possible situations, but *NEC* modeling should give you a good qualitative feeling for your particular situation. One common situation that I did not have time to examine experimentally is the case where the base is alongside the house but not too far from a corner. The conventional wisdom is that you should run the radials along the side of the house to the corner and then fan them out from there. I don't think that can hurt but keep in mind that the farther you are from the corner, the less effective this scheme is likely to be.

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¹Rudy Severns, N6LF, "Verticals, Ground Systems and Some History," *QST*, Jul 2000, pp 38-44.

